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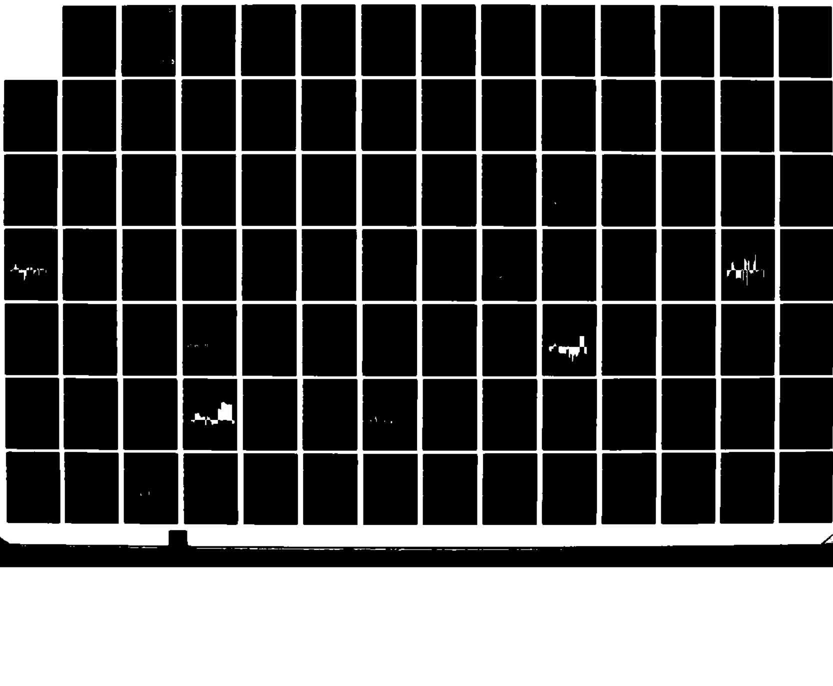

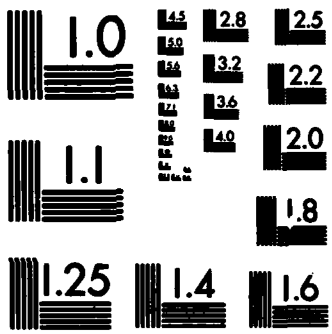

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ADAPT REPORT NO. 82

BEARING LUBRICANT INTERFACE MONITORING USING COMPOSITE SIGNATURE ANALYSIS

PREPARED BY

HERBERT E. HUNTER

AND

DAVID C. HUNTER

ADAPT Service CORPORATION

ADAPT SERVICE COF
P.O. BOX 5
READING MASS. C

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OFFICE OF NAVAL RESEARCH
800 N. QUINCY STREET
ARLINGTON, VIRGINIA 22217

AND

NAVAL AIR DEVELOPMENT CENTER
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents the results of the feasibility phase of a defense small business advance technology program (DESAT). The ultimate objective of the program is to improve and simplify engine failure prediction. This is to be accomplished by developing a series of objective algorithms which can use the results of standard engine monitoring measurements applicable to the bearing lubricant interface to detect,

identify and estimate the remaining life of worn engine components. The Phase I objectives which were successfully achieved and reported here were to: 1) identify the data which is currently available, 2) establish the procedures required to obtain it, and 3) to develop demonstration algorithms for a single aircraft engine type which would define the expected improvement in anticipating engine failures and illustrate the use of this approach. Specifically, of the 12 failures occurring in the data set available for the feasibility study, three were anticipated by current maintenance monitoring procedures and the remaining nine all were found as a result of preflight inspection or caused preflight or inflight aborts. The algorithms developed as part of this feasibility study would have anticipated all three of the failures identified by the present methods and would also have found seven of the nine failures which were missed by the current methods. Thus, assuming that the sample of engines utilized in this study is typical, current methods are anticipating approximately a quarter of the failures. Implementation of the failure detection algorithms developed in this study should increase this by a factor of three to the detection of approximately three quarters of the engine failures. Diagnostic, and time to failure algorithms are also demonstrated. Illustrations are provided showing how the unique products of an eigenvector analysis can provide more sophisticated analysis tools which may improve the Phase I performance even farther. The use of these algorithms in a "user-friendly" automated system is described.

ACKNOWLEDGEMENT

The Phase I studies would not have been possible without the support of many groups who are concerned with the acquisition and archiving of maintenance data in the Navy. The authors wish to give particular thanks to Mr. Leon Stallings of NADC, Mr. Paul Piscopo, Naval Air Propulsion Center and Mr. Robert Yurko of Baird Corporation for their assistance in finding and understanding the potential sources of data. We wish to thank Mr. Ken Lewis of NAVAIR; Mr. Bill Booth and Mr. John Vetter of NAVWESA; Mr. Bill King NARF Norfolk and Sr. Chief Norberto Basilio AIMD, Powerplants for their assistance in obtaining the data for this study.

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1.0 INTRODUCTION

This report presents the results of the feasibility phase or Phase I of a defense small business advance technology program (DESAT). The ultimate objective of the program is to improve and simplify engine failure prediction. This is to be accomplished by developing a series of objective algorithms which can use the results of standard engine monitoring measurements applicable to the bearing lubricant interface to detect, identify and estimate the remaining life of worn engine components. The Phase I objectives which were performed in the study which is reported here were to: 1) identify the data which is currently available, 2) establish the procedures required to obtain it and 3) to develop demonstration algorithms for a single aircraft engine type which would define the expected improvement in anticipating engine failures and illustrate the use of this approach.

At present, there are a number of different programs under which measurements are performed which would be useful in monitoring the bearing lubricant interface in particular and the engine health in general. The five sets of these measurements which were considered in this study were: 1) the engine test cell measurements performed after major overall of the engine, 2) the concentrations of metallic impurities in the oil measured as part of the Naval Oil Analysis Program (NOAP), 3) the Navy Maintenance and Material Management information reports (3M), 4) the Inflight Engine Condition Monitoring System (IECMS) data, and 5) preflight inspection data.

Upon the successful completion of Phase I which is reported in this report, it is anticipated that a Phase 2 program will be implemented with the objectives of: 1) developing and executing a demonstration that will prove the gain suggested by these feasibility studies, 2) refining the accuracy of the estimated performance gains and 3) providing performance gain versus cost trade-off information. The Phase 2 plans will be the subject of a separate document, however, the present report provides the basis upon which these Phase 2 plans will be developed.

The present report begins with a summary of the major results, conclusions and recommendations. This summary presented in Section 2.0 shows the results of the feasibility study without

presenting a description of the methodology or justifying the results. The recommended incipient failure detection and analysis system resulting from this study is also included at the end of this summary of results, conclusions and recommendations. The description methodology and justification of the results is presented in the remaining sections and the appendices. Section 3.0 describes the data acquisition and preparation which was required for the feasibility study. This is followed by a section describing the development, analysis and expected performance of the failure analysis algorithms. The details of the ADAPT approach to empirical analysis are given in the appendices.

2.0 SUMMARY OF RESULTS, CONCLUSIONS AND RECOMMENDATIONS

The major result of this study is the verification of our anticipated result stated in the Phase I proposal as, "At the conclusion of the Phase 1, we will have shown the feasibility of improving bearing lubricant interface wear monitoring and, thereby, reducing the number of castrophic engine failures by signature analysis of composite signatures of several wear sensor measurements". Specifically, of the 12 failures occurring in the data set available for the feasibility study, three were anticipated by current maintenance monitoring procedures and the remaining nine all were found as a result of preflight inspection or caused preflight or inflight aborts. The algorithms developed as part of this Phase 1 feasibility study would have anticipated all three of the failures identified by the present methods and would also have found seven of the nine failures which were missed by the current methods. Thus, assuming that the sample of engines utilized in this study is typical, we conclude that current methods are anticipating approximately a quarter of the failures and that implementation of the failure detection algorithms developed in this study should increase this by a factor of three to the detection of approximately three quarters of the engine failures. Clearly, this is a significant improvement.

In addition to the improvement in the performance, the proposed algorithms will be implemented in a fully automated and interactive mode. Information is currently available from the individual measurement programs usually in the form of raw data. The proposed algorithms will automatically combine all of this information and output an answer instead of the results of the testing. For example, in the oil program, the processing and recording of the concentrations of the oil sample is handled entirely by automated test equipment and computers. The result is a printed table of the concentrations of the metallic impurities plus a "lab advice" code. If the ADAPT algorithms were utilized, this same information would be combined with the results of the test cell

run at the time the engine was last overhauled (also processed and recorded by computers for many engines*) and applicable 3M data in the computer . The result would be a print-out indicating that the engine was healthy or that a failure could be anticipated and for the more common failures a diagnosis of the most likely component to fail. In many cases, an estimate of the time remaining before the failure occurs will also be made.

This answer will be followed by the display of a menu which the user may use to obtain additional information if desired. Thus, from the users point of view, the proposed approach will yield answers which require no further analysis to determine the corrective action, if any, which is required. Along with this gain in user "friendliness", one can anticipate finding three times as many failures as are currently being found.

2.1 Conclusions

Considerable additional detail of these results as well as the development of many other significant conclusions are described in Section 4.0, Development Analysis and Expected Performance of Failure Analysis Algorithms. Specifically, the development and analysis of the expected performance has shown:

1) The data currently obtained by existing measurement programs contains much unused information which is sufficient to triple the number of failures anticipated relative to current procedures. It is anticipated that this will result in a very significant reduction in preflight and inflight aborts as well as reduce the number of problem engines which leave the test cell.

2) The data required to develop these algorithms and to apply them is available from standard Navy data archival sources.

3) Most engine failures called by the ADAPT algorithms are called 20 to 160 engine hours in advance of the actual occurrence of the failure.

4) A demonstration algorithm for predicting the time to failure F3 was developed and showed a capability to predict the time at which the failure would occur from 160 engine hours in advance of the failure to the occurrence of the failure with a 3 sigma error of ± 18 engine hours.

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* At Norfolk, one automated test cell became operational in Jan. 1982 and the second is expected in the near future.

5) Both simple to use go-no-go algorithms which printout the engine health and the action required and more sophisticated lab analysis procedures were demonstrated.

6) The algorithms required for both the simple go-no-go procedures and the more sophisticated analysis procedures can all be implemented in any one of three ways from a hardware standpoint. These three ways are: 1) on the existing NOAP computer, 2) on the existing computer in the automated test cell or 3) on a stand alone low cost microcomputer.

7) As a result of the analysis of the relative importance vectors, we have concluded that there is a cleanup mechanism which we were previously unaware of which allows the metallic contaminants to indicate the presence of non-metallic contaminants.

8) It can be anticipated that the addition of a larger training set of engines will improve the overall performance of these algorithms relative to that shown in these feasibility studies.

9) A significant, but expected difference was observed between data vectors constructed from manual and automated test data. This difference was sufficiently small that it does not mask the engine health information.

2.2 Recommendations

Based on successful achievement of all of the Phase I objectives and demonstration of the potential for signficant improvement in detecting potential aircraft engine failures, it is recommended that Phase 2 of the bearing lubricant interface health monitoring using integrated composite signature analysis, be implemented and directed towards achieving the following:

1) Develop and implement a six month demonstration of the recommended incipient failure detection system for the TF30 engine at Norfolk Naval Air Station. Specifically, this would include: a) incorporation of revised incipient failure detection and diagnostic algorithms in either the NOAP computer, the test cell computer and/or a stand alone microcomputer, b) the integration of these procedures into the existing organization, c) the presence of ADAPT personnel during the six month demonstration to insure proper implementation and train Navy personnel in its use and d) the evaluation of the effect of the implementation of both the fully automated system and the detection and analysis support system on the number of the inflight and preflight aborts occurring.

2) To build a cost effectiveness computer model to demonstrate the usefulness of this concept for other engines, data sets and facilities.

3) To integrate the Inflight Engine Condition Monitoring System (IECMS) data into the analysis to determine what improvement is possible for the IECMS equipped aircraft using the data used for this study and the ADAPT data analysis procedures.

4) Perform analysis of relative importance vectors to determine how the costs may be reduced and performance improved by modifying the data collection and recording procedure.

2.3 Recommended Incipient Failure Detection and Analysis Demonstration System

The incipient failure detection demonstration software packages will be implemented in the existing NOAP data gathering hardware and/or the automated test cell. They will contain two completely independent user oriented systems: 1) the automated failure detection system and 2) the detection and analysis support system. They could also be implemented in a low cost stand alone microcomputer, but this is not recommended unless an unforeseen problem arises with implementing it in the existing hardware. To illustrate the concept, we shall describe a system implemented in the NOAP data gathering hardware. The modification required for implementation in the automated test cell or a stand alone unit would be straightforward and would not change this description significantly from the users viewpoint.

The system would incorporate: 1) a capability to use the existing NOAP data files, 2) input the test cell results (preferably directly in computer compatable format), 3) accept computer compatable copies of the 3M data being submitted by NAS Norfolk to the 3M data base, 4) the ADAPT derived algorithms and 5) the ADAPT interactive scatter plot and relative importance vector analysis tools. As each new test cell data set or oil sample is added, this software package would: 1) update the data vector for the engine effected, 2) apply the algorithms to the updated data vectors, 3) printout a message defining the engine health and 4) display a menu which the user may use to request additional information and analysis.

The message defining the engine health would state either failure is anticipated or a failure is not anticipated. If a failure is anticipated, the printout would also include the results of the application of the diagnostic and time to failure algorithm. For most failures, this would define the system where the failure is most likely to occur. For the more

on failures, the exact failure should be defined and in
cases the expected engine hours left to failure would be
ted out.

Thus, instead of the current printout of test results
a suggested lab advice for the NOAP data and separate
tout of the test cell results at the test cell, the user
d see a printout such as: "Engine Serial No -701251 on
Serial No-160899 shows no indication of incipient failure
d on test cell data of 15 July 1983 and oil samples taken
ugh 21 September 1983".

If an engine failure were about to occur, the user would
lerted by a message of the follwing form:

CAUTION Engine Serial No-701251 is expected to
in the near future. Analysis indicates:

1) Failure will occur in the afterburning fuel system.

2) Most likely component to fail is the injector nozzle
a probability of 0.76.

3) If the failing component is the injector nozzle, the
ined probability that the engine will operate an additional
ours without failure is 0.75.

Either of the preceding messages will be followed by a
pt asking if the user desires additional information. If
user replies in the affirmative, a menu will be displayed
which the user may elect to display and/or print any or
of the pertinent test cell, NOAP or 3M data as well as the
T scatter plot or relative importance vector analysis
lays which are described in Section 4.1 of this report.
selection will be accomplished by placing the cursor on
desired menu item and executing a carriage return. Thus,
ng skill will <u>not</u> be important to using this system.

3.0 DATA ACQUISITION AND PREPARATION

This section summarizes: 1) the selection of the data, 2) the verification performed on the data, and 3) the integration of the data from the various sources into the data vector.

3.1 SELECTION OF DATA

The Data acquisition study considered five sources of data which were anticipated to be available from various archiving systems within the Navy. These five sources of data were: 1) test cell results after engine overhaul, 2) Naval Oil Analysis Programs (NOAP), 3) Navy Maintenance Material Management (3M) data base, 4) flight line and in-flight recorded data and 5) Inflight Engine Condition Monitoring System (IECMS) data. Review of the availability and applicability of these data sets for the present studies indicated that the first three data sources were readily available and typical of data that could be found on other engines and at other facilities.

A review of the procedures used at the flight line to record information indicated that at the Norfolk facility a limited amount of information was recorded concerning the number of flights, exhaust gas temperature and oil usage. However, the procedures for these would clearly vary from squadron to squadron and facility to facility within the Navy. Also, the quality of the data would be dependent upon the individual who was recording the data. For these reasons, it was felt that this flight line information even where it was available at Norfolk would not be a good type of information to be included in the study.

The IECMS data was not available on any of the aircraft at Norfolk. The IECMS data is also only available on a limited number of aircraft and the cost of obtaining IECMS data was considerably more than the cost of obtaining the other data which was considered in this study. Furthermore, it appeared as though the procedures required to obtain the IECMS data required for this study might not be accomplished within the six month available for the study. However, it must be emphasized that this IECMS data is archived and is available for future use, however, some processing may be required to obtain the data in a useful format. Because of the significantly greater cost per aircraft to obtain IECMS data under operational

conditions, the time and resource constraints on the Phase 1 study, it was felt that the most useful Phase 1 program would be to determine the improvement in maintenance performance which can be achieved without the installation of the IECMS system on aircraft. Phase 2 studies can be performed to evaluate the additional improvement possible both relative to the non-IECMS equipped aircraft using the methods developed in this study and relative to the IECMS aircraft which did not use the methods developed in this study or the additional data.

Thus, the Phase 1 studies constructed the data vector using: 1) the test cell data obtained after the most recent engine overall, 2) the NOAP data and 3) the 3M data. The specific components to be derived from each of these three data sources are shown in Table 1. The following subsections will discuss how each of these data were verified and prepared for incorporation into the data vector.

3.2 TEST CELL DATA

The availability and usefulness of the test cell data for this study became apparent during the ADAPT Service Corporation's fact finding visit to the Norfolk Naval Air Station and overhaul facilities. At the time of this visit, an automated data recording system with a limited analysis capability had just become operational in one of the two test cells used to perform tests on the engines after the overhauls. It was anticipated that a similar automated system would become available in the second test cell within a year. We were also informed that when an engine was received for overhaul, the results of the previous test cell tests were still attached to the engine's log. Since this data would be replaced with the new test cell results, it was the standard procedure to remove the old test cell data from the log destroy it and replace it with the new test cell information. This procedure offered an excellent opportunity to obtain the test cell data which would be pertinent to the entire time period between overhauls and for which the NOAP and 3M data would also be available.

Thus, our recommended plan was to ask the Norfolk test cell personnel to retain the old data rather than destroy it and send it to us for use in this program. We would then supplement this data with the NOAP and 3M data to construct the data vectors. An exploratory set of data was obtained to test out this system and this information was obtained on the

TABLE - 1

TEST CELL DATA VECTOR COMPONENTS

INDEX	PARAMETER
1	Engine Series Code
2	Lube Spec. Code
3	Test Spec. Code
4	Fuel Spec. Code
5	Total Test Time
6	Number of Starts
7	Barometric Pressure
8	Accel Time-Idle to Int
9	Accel Time-Int to Max
10	Accel Time-Max to Int
11	Accel Time-Idle to Max
12	Stage Bleed Close Pres.
13	Stage Bleed Open Pres.
14	Max TT5 During Start
15	Time to Idle
16-19	Inlet Pressure PT2
20-23	Inlet Temperature TT2
24-27	N1 Turbine Speed
28-31	N2 Turbine Speed
32-35	TT5
36-39	Fuel Flow
40-43	PS3
44-47	PS4
48-51	PCP
52-55	PT7
56-59	PS3/PT2
60-63	PS4/PS3
64-67	PS4/PT2
68-71	PCP/PS4
72-75	N1/N2
76-79	PT7/PT2
80-83	DIF**(TT5)
84-87	DIF**(PS4/PT2)
88-91	DIF**(PS3/PT2)
92-95	DIF**(N1)
96-99	DIF**(N2)
100-103	DIF**(WF)
104-107	Vib.-Inlet Case
108-111	Vib.-Difference Case
112-115	Vib.-Turbine Case
116-119	Oil-Main Pres.
120-123	Oil-Breathe Pres.
124-127	Oil-In. Temp.

* 4 Values each for idle, intermediate, zone 3 and zone 5 (Maximum After-burner) test condition.

** DIF = Measured Value - Expected Value

OIL ANALYSIS (NOAP) DATA VECTOR COMPONENTS

INDEX	PARAMETER
128-135	FE Conc.*
136-143	AG Conc.*
144-151	AL Conc.*
152-159	CR Conc.*
160-167	CU Conc.*
168-175	MG Conc.*
176-183	TI Conc.*
184-191	PB Conc.*
192-199	SN Conc.*
200-207	NI Conc.*
208-215	MO Conc.*
216-223	SI Conc.*
224-231	NA Conc.*
232-239	BA Conc.*
240-247	CD Conc.*
248-255	MN Conc.*
256-263	V Conc.*
264-271	ZN Conc.*
272	Eng. Hr. Since Oil Chg.
273	Eng. Hr. Since Test Cell
274	Days Since Oil Chg.
275	Day Since Test Cell

* 8 Values each @ test cell, test cell - 50 hr, last oil chg. last oil chg - 50 hrs, last 75, 50, 25 hrs and present

3M - DATA VECTOR COMPONENTS

INDEX	PARAMETER
276	Total Maint. Man Hrs
277	Last 100 hr, Maint. Man Hrs.
278-287	Number of Occurences of 10 Most Active Work Unit Codes*
288-297	Number of Occurences of 10 Most Active Work Unit Code, in Last 50 hrs*
298-317	Number of Occurrences of 20 Most Active Malfunction Description Codes*
318-337	Number of Occurrences of 20 Most Active Malfunction Description Codes in last 50 hrs *
338-351	Number Of Occurrences of Action taken Codes 9, A,B,C,J,K,P,Q,R,S,T, Y and Z *
352-365	Number of Occurrences of Action Taken Codes in Last 50 hrs
366-375	Number of Occurrences of 10 Most Active Discovered Codes
376-385	Number of Occurrences of 10 Most Active discovered Code in last 50 hr

* One Index reserved for "other"

first three engines. It was then used to specify the remainder of the data. The system worked well and it was determined that this method would be used.

Unfortunately, when similar information was requested on a second and larger set of engines, it was discovered that the old data was no longer available with the engines arriving at the test cell. Thus, our procedure had to be changed to utilize more recent test cell data (i.e. copies of the current test cell data) then originally anticipated. The effect of this change in the availability of data was that only two of the engines which were used for this study had data available over the entire time period between two successive entries to the test cell. The remaining engines had significantly shorter time periods of data and often all of the data for a given engine represented only good or only failing cases.

The automated test cell data was archived from the time that the test cell first became operational in January 1982. This data was also used in this study. Thus, the test cell parameters were obtained from both the automated system and manual recorded data. A study was performed to determine the effect of mixing both manually recorded and automated test cell data. The conclusions of this study were that although there were measurable differences between these data, they were not a detriment to the present study. In fact, a large portion of this difference would probably disappear with a larger sample of engines. These results will be developed and discussed in more detail in Section 4.5 after we have introduced the ADAPT analysis techniques used for the study.

For both the automated test cell and the manually recorded data, the information was supplied in hardcopy format. Thus, all of the variables used were hand punched. For a number of the manually recorded cases, there was also the problem of missing data. To minimize the effect of keypunching errors and to account for missing data, all of the data after punching was processed through a program which tested the data for missing values and for unusual values indicating keypunching errors. The program incorporated in it the nominal performance curves for the engine. These nominal performance curves were used to construct the difference parameters between the expected and observed performance which are included in variables No. 80 through 103 in Table 1. For those cases where data was missing, these curves were also used to estimate the missing data. In this case, the associated difference variable would be zero. However, by using this approach,

missing data did not create large perturbations in the data vector and thus the effect of missing data was minimized.

To further minimize the effect of potential keypunch errors, all of the data was plotted on performance curves such as those shown in Figures 1 through 6. On these curves, each of the symbols represents an engine at a specified test condition. The variables used in the data vector were those obtained at the idle, intermediate, Zone 3 and maximum afterburner test conditions. Thus, for each of the engines, there are four points on the performance curves. The cross hatched area on Figures 1 through 6 shows the acceptable performance as defined by the manufacturer for the TF30 engine. The solid line is the nominal performance which was used to calculate the differences appearing in variables 80 through 103 on Table 1.

By examining preliminary plots such as those shown in Figures 1 through 6, any significant keypunched errors could be detected and corrected prior to construction of the data vectors. This was accomplished and the results presented in Figures 1 through 6 are the performances after the significant keypunch and data omissions have been corrected. It should be noted that the acceptable performances shown on these figures by the cross hatched bands are those without the after burner operating. For some of the parameters, especially the fuel consumption shown in Figure 6, this performance is very different for the half of the cases shown during which the after burner was operating. In fact, in this figure the three clusters occurring on the right hand side are those associated with no after burner operating those with the after burner in Zone 3 and the highest fuel rate those with the maximum after burner.

3.3 NOAP DATA

The NOAP data was converted from it's archival form to a format which is compatable with the ADAPT programs. This involved a conversion of the data to the IBM internal machine format and the arranging of the data by engine, sorted on the date and engine hours since overhaul. Throughout the data acquisition process, the engine hours since overhaul is used as the reference time frame and often referred to as simply engine hours.

After the NOAP data has been changed to the ADAPT format, the second phase of the data acquisition is the self check phase. The verification of the NOAP data is done in three ways: 1) the clear and orderly displaying of the data, 2) software scanning for logical inconsistencies and 3) intelli-

FIGURE - 1

PERFORMANCE CURVE TT5/THT2 VS. PT7/PT2

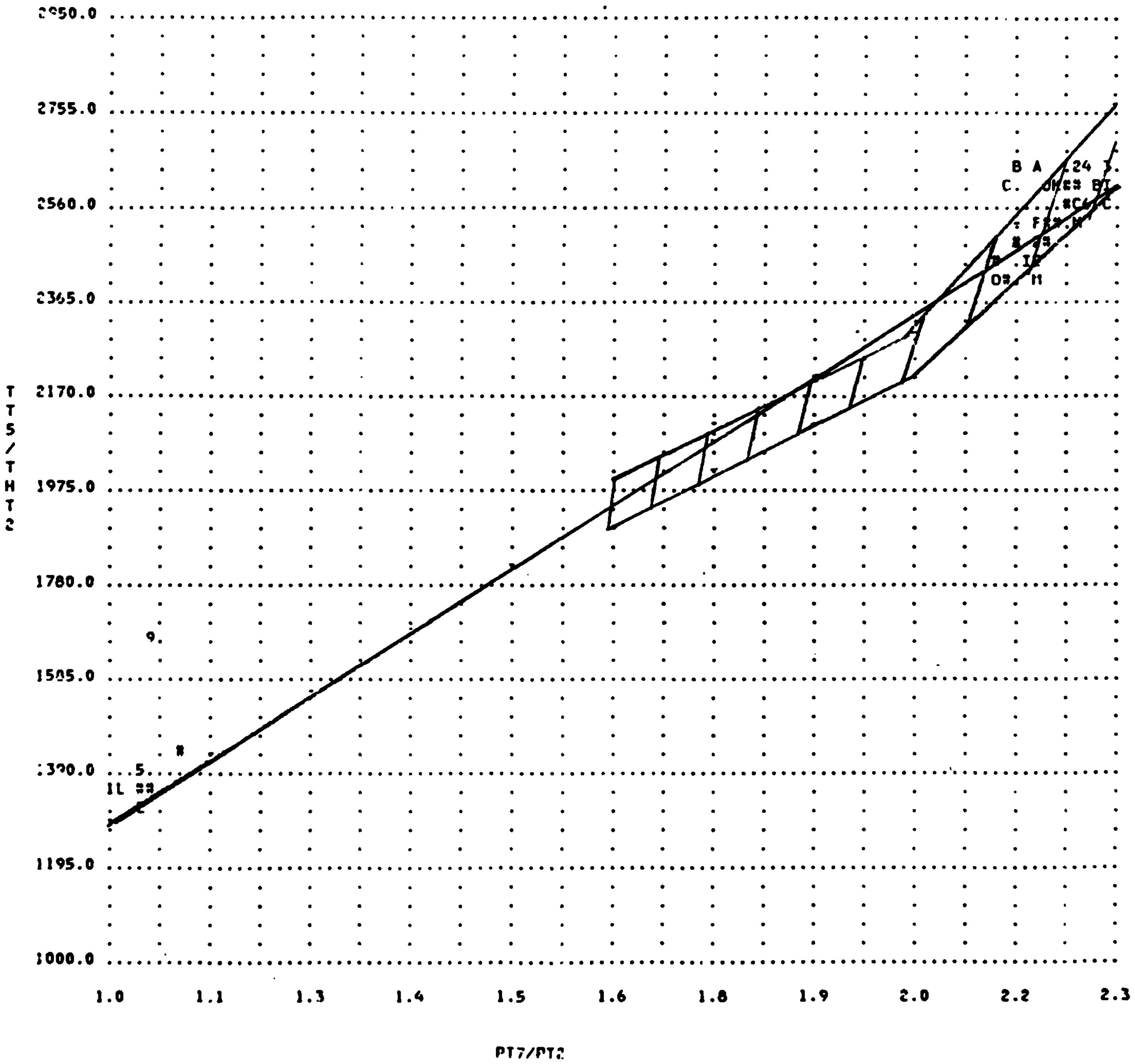


FIGURE - 2

PERFORMANCE CURVE PS4/PT2 VS. PT7/PT2

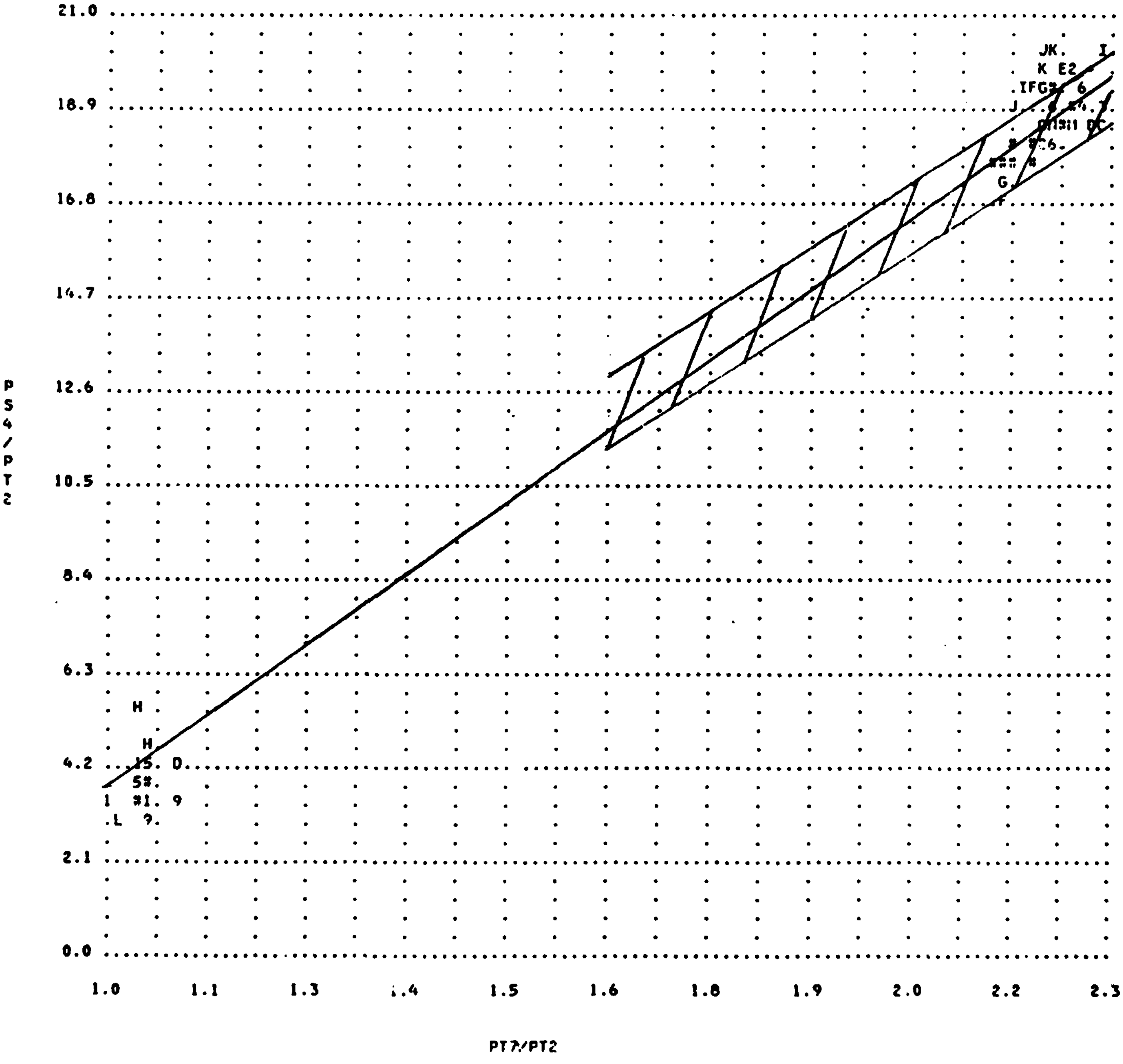


FIGURE - 3

PERFORMANCE CURVE PS3/PT2 VS. PT7/PT2

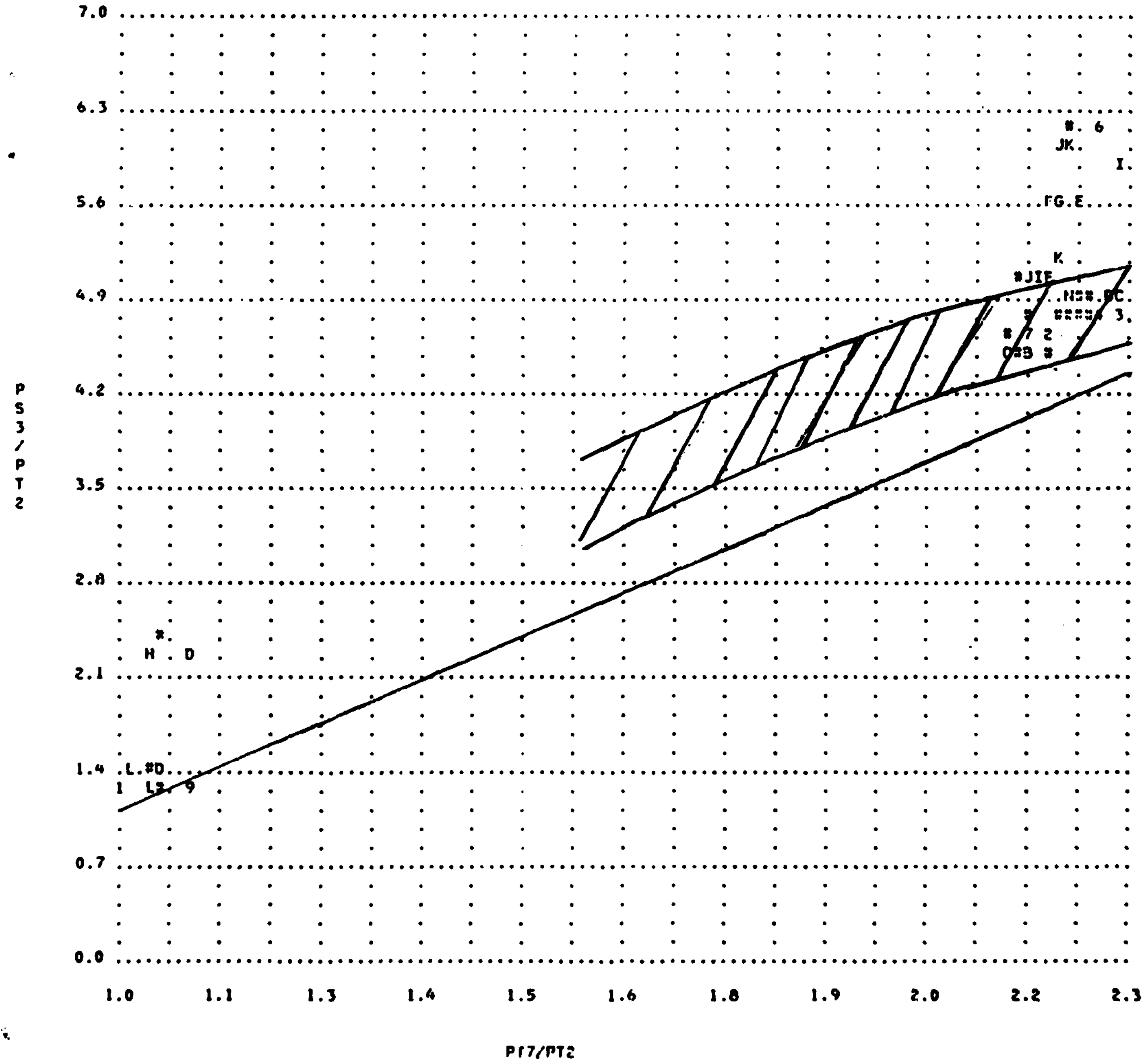


FIGURE - 4

PERFORMANCE CURVE N1/SQ(THT2) VS. PT7/PT2

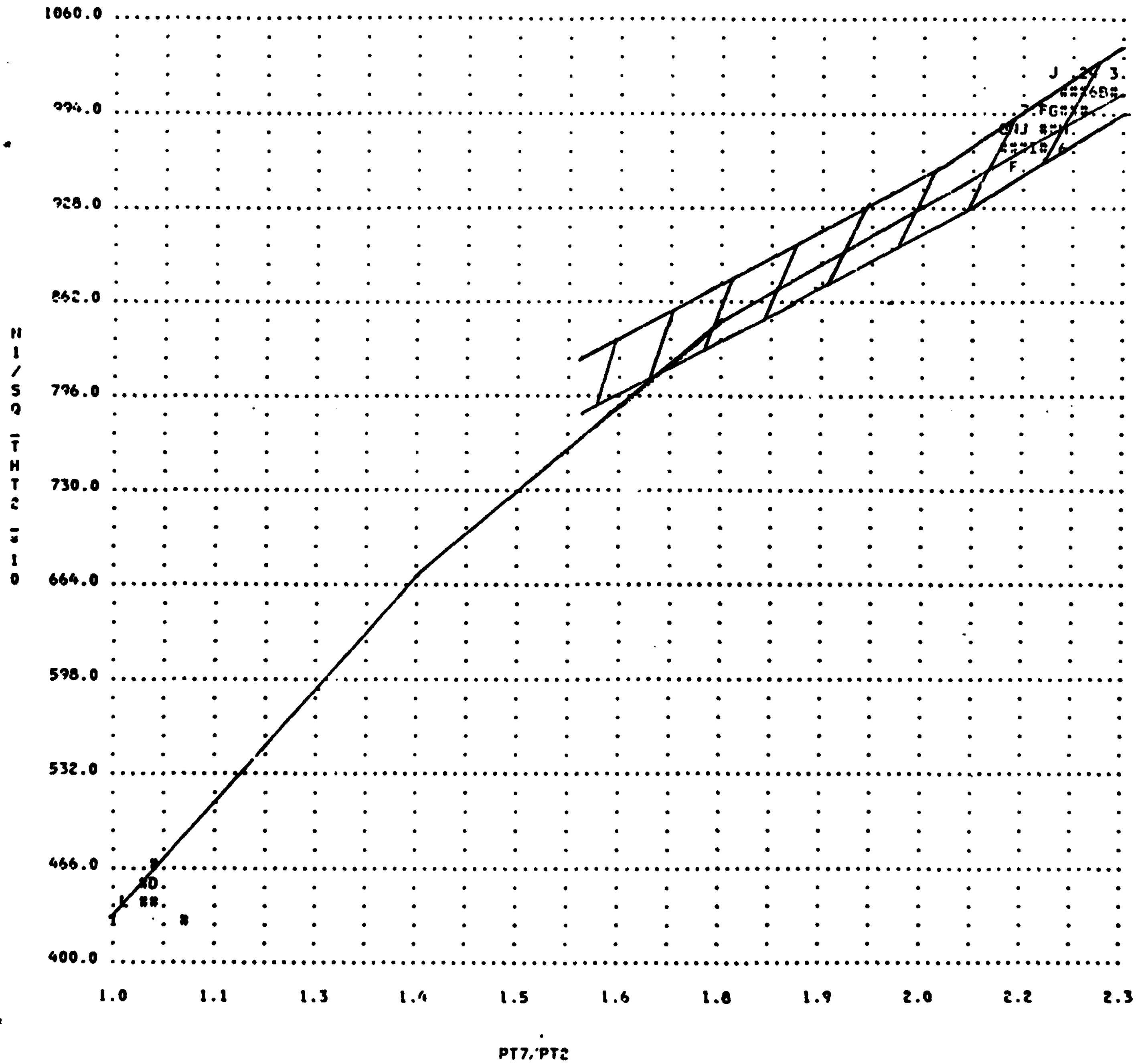


FIGURE - 5

PERFORMANCE CURVE N2/SQ(THT2) VS. PT7/PT2

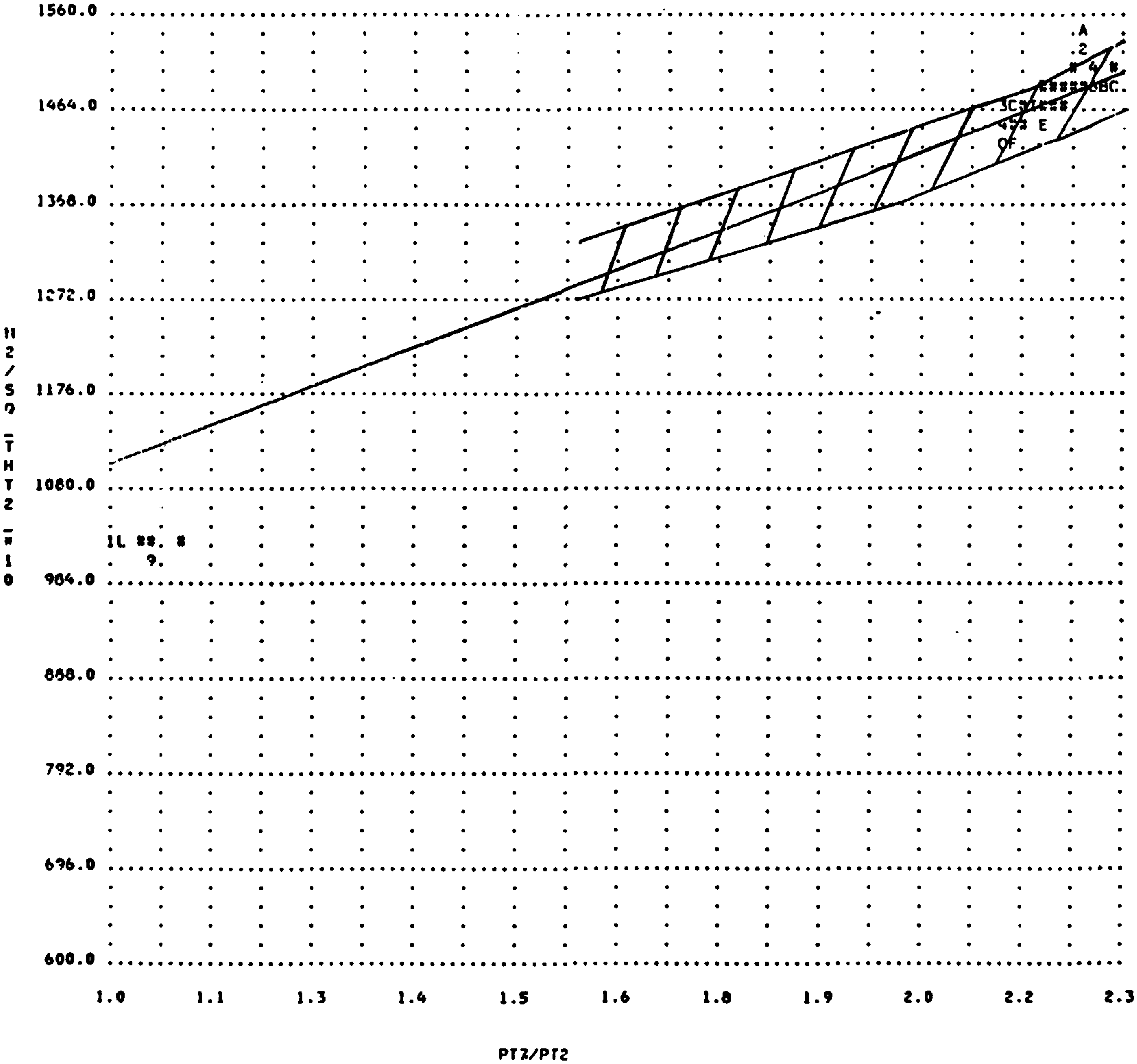
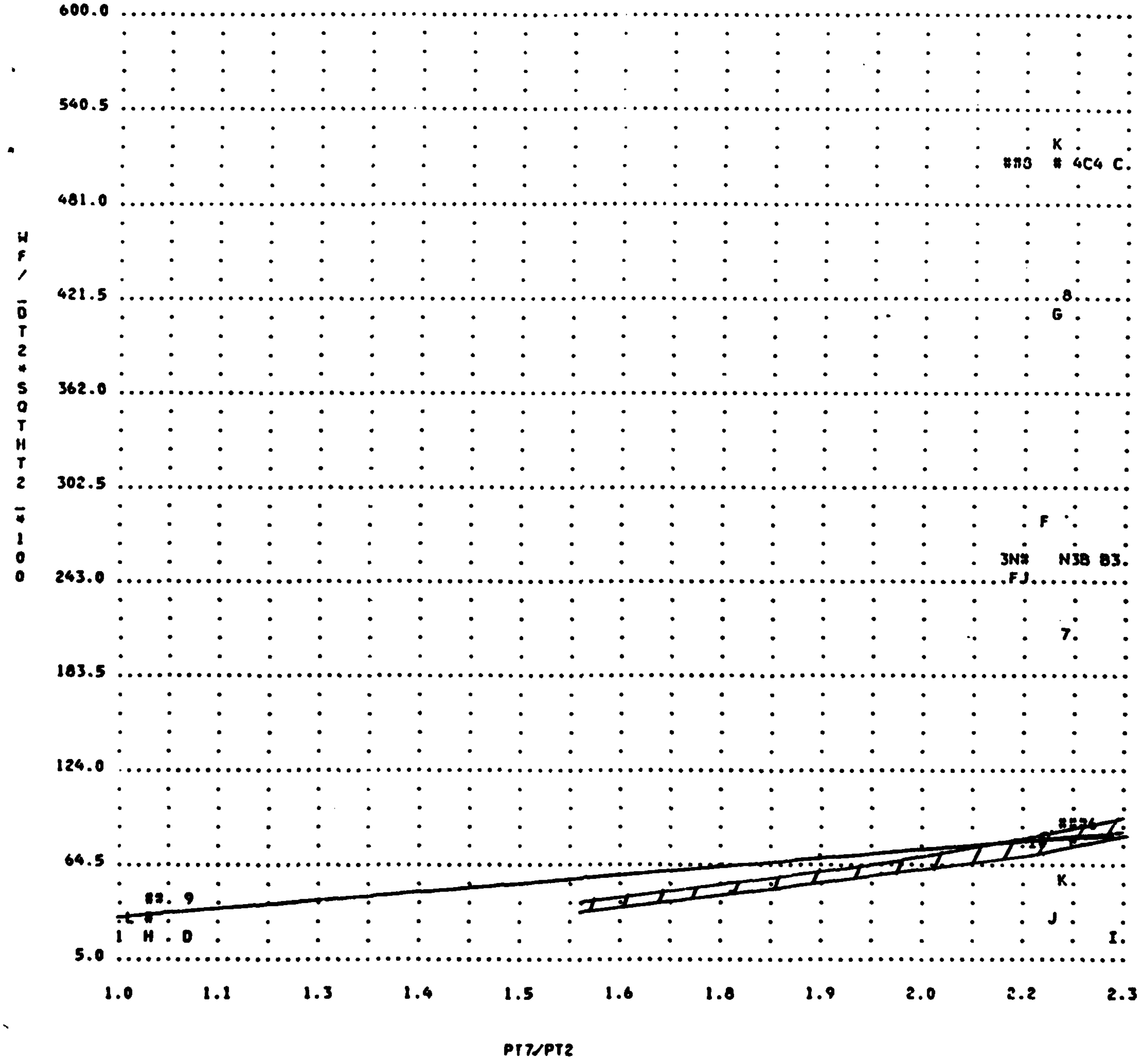


FIGURE - 6

PERFORMANCE CURVE WF/(DT2*SQTHT2) VS PT7/PT2



gent automated correction of data.

The NOAP data is displayed in a concise chronological report so that any abnormalities can easily be spotted. To aid in spotting abnormalities, each oil sample is tested for specific logical faults, they are: 1) engine transfer to a second aircraft while in operation, 2) unusual aircraft type, 3) unusual engine type, 4) negative engine hour progress and 5) the change in engine hours since last overhaul greater than ten hours different from the change in engine hours since last oil change. The flagging of one or more of these conditions does not necessarily indicate a bad sample; for example, if the hours since last oil change decreases while the hours since last overhaul increases an oil change probably occurred. This information is used to calculate a date for the most recent oil change throughout the engines life. It was found that the NOAP data often had "unknown" values for the hours since overhaul and oil change as well as the days in transit. The program scans for these "unknown" values and replaces them with either the average value or interpolates the value between neighboring values. The program will also determine if the hours since overhaul and hours since oil change have been interchanged and correct for that error. Whenever one of these corrections is made, the corrected item is flagged to indicate the correction.

Figure 7 is an example of the NOAP data report generated in the data acquisition phase for each engine there are two sections: 1) the sample summary section, in this section the environment of each sample is displayed as well as the warnings and flags discussed above and 2) the wear metal concentration section. In this section, the date, engine hours and wear metal concentrations (ordered left to right the concentration are Fe, Ag, Al, Cr, Cu, Mg, Ti, Pb, Sn, Ni, Mo, Si, Na, Ba, Cd, Mn, V, Zn, are displayed chronologically.

In Figure 7, for sample Number 422, the lab code is blank in the sample summary section. This indicates the data was obtained from a NOAP computer summary sheet produced at Norfolk and the last six mineral concentrations were, therefore, not available. The six values shown in the wear metal concentration section for sample 422 were, therefore, obtained from the average of test cell concentrations. In future studies, the numbers could be refined by using a larger data set and averages appropriate to the case. However, it is anticipated that this problem will not exist in Phase II since the data archived in San Antonio has all 18 measurements. The Norfolk data was used in the present study because of the time lag in the San Antonio data combined with the tight schedule of this program and the limits on the availability of test cell data.

FIGURE - 7

Sample Summary Section

ENGINE SERIAL NUMBER: 701264 AIRCRAFT SERIAL NUMBER: 135010

415 ANALYSIS DATE: 2084 3/25/82
SAMPLE DATE: 2083 3/24/82
LAB CODE: ANE
HRS. SINCE OVERHAUL: 605
HRS. SINCE OIL CHANGE: 0
DATE OF LAST OVERHAUL: 82083.0
DATE OF LAST OIL CHANGE: 82083.0
REASON: TEST CELL
LAB RECOMENDATION: A
DAYS IN TRANSIT: 1
SAMPLE NUMBER: 217
WARNING AIPCRAFT TYPE IS TEST NOT F14A

418 ANALYSIS DATE: 2141 5/21/82
SAMPLE DATE: 2138 5/18/82
LAB CODE: ANE
HRS. SINCE OVERHAUL: 666
HRS. SINCE OIL CHANGE: 62
DATE OF LAST OVERHAUL: 82083.0
DATE OF LAST OIL CHANGE: 82083.0
REASON: ROUTINE
LAB RECOMENDATION: A
DAYS IN TRANSIT: 3
SAMPLE NUMBER: 57
WARNING AIRCRAFT SERIAL NUMBER CHANGED AND THE ENGINE SERIAL NUMBER DIDN'T
ENGINE SERIAL NUMBER = 701264 AIRCRAFT SERIAL NUMBER = 160398

420 ANALYSIS DATE: 2159 6/ 8/82
SAMPLE DATE: 2158 6/ 7/82
LAB CODE: ANE
HRS. SINCE OVERHAUL: 676
HRS. SINCE OIL CHANGE: 72
DATE OF LAST OVERHAUL: 82083.0
DATE OF LAST OIL CHANGE: 82083.0
REASON: ROUTINE
LAB RECOMENDATION: A
DAYS IN TRANSIT: 1
SAMPLE NUMBER: 86

422 ANALYSIS DATE: 2180 6/29/82
SAMPLE DATE: 2176 6/25/82
LAB CODE:
HRS. SINCE OVERHAUL: 683
HRS. SINCE OIL CHANGE: 79
DATE OF LAST OVERHAUL: 82083.0
DATE OF LAST OIL CHANGE: 82083.0
REASON: ROUTINE
LAB RECOMENDATION: A
DAYS IN TRANSIT: 4
SAMPLE NUMBER: 0103

Wear Metal Concentration Section

415	82083.0	0.0	605.0	1.0	0.0	0.0	0.0	0.0	1.0	1.0	0.0	8.0	1.0	1.0	1.0	0.0	0.0	9.0	0.0	0.0	0.0
418	82138.0	62.0	666.0	1.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0	7.0	0.0	1.0	2.0	0.0	0.0	8.0	0.0	0.0	0.0
420	82158.0	72.0	676.0	3.0	1.0	0.0	0.0	0.0	5.0	1.0	0.0	6.0	0.0	0.0	3.0	2.0	0.0	22.0	0.0	0.0	0.0
422	82176.0	79.0	683.0	1.0	0.0	0.0	0.0	0.0	1.0	1.0	0.0	7.0	0.0	0.0	3.0	1.1	0.1	3.9	0.3	0.0	0.1

Samples 412 and 418 in the sample summary section both ve warning examples, sample 415 indicates that the air- aft type indicated was "test" instead of the normal F14A. is warning generally occurs on test cell samples and this se is not an exception since the reason for the sample is splayed as "TEST CELL". The warning occurring on sample 8 occurred because when the test cell was performed the rcraft the engine was to be placed in was not known, erefore, the correct aircraft serial number could not be ed.

The automated data acquisition program as described ove was used in conjunction with a manual two pass technique ere the results from the automated first pass was studied d then corrected where necessary using information from e test cell and 3M data.

4 3M DATA

The 3M data was converted to the IBM internal machine rmat and sorted on engine and date in the process of data quisition. A concise summary of the 3M data was printed r each maintenance entry, each entry printed the work unit ading, the work unit subheading and the work unit title as n be seen in the example Figure 8. There are multiple tries for the "HOW MALFUNCTIONED CODE", the "ACTION TAKEN DE" and the "WHEN DISCOVERED CODE". These occur because the des appear at several locations in the archival records.

The 3M data is scanned by the software for the following gical faults: 1) engine transfer to a second aircraft ile in operation and 2) work unit information missing. If e of these faults is discovered a warning message is printed thin the maintenance entry it was found.

5 INTEGRATION INTO TRUTH DATA AND DATA VECTOR

The final step in the data acquisition process is to mbine the three sources of data into the data vector shown Table 1. This data vector is created for any date requested om the available data on the engine requested. Three steps e used in the creation of the data vector. First the different urces of data are calibrated to the same reference time (engine urs). Next the values for the data vector are calculated for e date requested, and finally the data vector is checked for normalities.

FIGURE - 8

ENGINE SERIAL NUMBER: 701264 AIRCRAFT SERIAL NUMBER: 160398
INCIDENT DATE: 82090 3/31/82
REMOVED PART NUMBER:
INSTALLED PART NUMBER:
WORK UNIT HEADING: IGNITION SYSTEM
WARNING WORK UNIT SUBHEADING NOT FOUND
WORK UNIT TITLE: EXCITER INPUT CABLE
WORK UNIT CODE: 23BA700
HOW MALFUNCTIONED CODE: 020
HOW MALFUNCTIONED CODE: 020
HOW MALFUNCTIONED CODE: 000
ACTION TAKEN CODE: B
ACTION TAKEN CODE: B
ACTION TAKEN CODE: 0
WHEN DISCOVERED CODE: H
WHEN DISCOVERED CODE: H
MAN HOURS: 000005

ENGINE SERIAL NUMBER: 701430 AIRCRAFT SERIAL NUMBER: 701430
INCIDENT DATE: 82064 3/ 5/82
REMOVED PART NUMBER:
INSTALLED PART NUMBER: 754495
WORK UNIT HEADING: EXHAUST SECTION
WORK UNIT SUBHEADING: AFTERBURNER DIFFUSER ASSEMBLY
WORK UNIT TITLE: AFTERBURNER DIFFUSER ASSEMBLY
WORK UNIT CODE: 23B4400
HOW MALFUNCTIONED CODE: 799
HOW MALFUNCTIONED CODE: 799
HOW MALFUNCTIONED CODE: 000
ACTION TAKEN CODE: Q
ACTION TAKEN CODE: Q
ACTION TAKEN CODE: P
WHEN DISCOVERED CODE: 0
WHEN DISCOVERED CODE: 0
MAN HOURS: 000003

INCIDENT DATE: 82068 3/ 9/82
WARNING AIRCRAFT SERIAL NUMBER CHANGED AND THE ENGINE SERIAL NUMBER DIDN'T
ENGINE SERIAL NUMBER = 701430 AIRCRAFT SERIAL NUMBER = 160899
REMOVED PART NUMBER:
INSTALLED PART NUMBER:
WARNING WORK UNIT HEADING NOT FOUND

WARNING WORK UNIT SUBHEADING NOT FOUND
WORK UNIT TITLE: IGNITION SYSTEM
WORK UNIT CODE: 23B0000
HOW MALFUNCTIONED CODE: 800
HOW MALFUNCTIONED CODE: 800
HOW MALFUNCTIONED CODE:
ACTION TAKEN CODE: Q
ACTION TAKEN CODE: Q
ACTION TAKEN CODE:
WHEN DISCOVERED CODE: 0
WHEN DISCOVERED CODE: 0
MAN HOURS: 000011

The calibration of the data sources is done with respect to the engine hours since overhaul for the NOAP, test cell, and the 3M data. In order to calculate the engine hours of a particular 3M or test cell data entry, the date is used to interpretate an estimate of engine hours.

The calculation of the data vector points varies from point to point. For points 1 through 127, the test cell data is used as described in Section 3.2. Points 128 through 271 involve linearly interpolating between available wear metal contractions in order to obtain the concentration at the observation date. To keep this interpolation from causing unreasonable results through large extrapolations, average values of the wear metal concentrations at test cells have been used. If no test cell data was available, and if dates latter than the lattest available data are requested, the lattest concentrations available are used instead of the extrapolated values. Points 272 through 275 are interpreted from available data. The 3M data Points 276 through 385 are calculated by counting the occurrences of the required codes. In the cases which indicate a number of hours should be counted back, the date corresponding to that number of hours in the past is calculated through interpolation and becomes the starting point for the counts. The most active codes were calculated using the initial data received. This data was limited in the number of cases it contained and in future study these most active codes should be recalculated on a larger data set.

In the process of this study, a possible problem with the interpolation used was encountered which should be addressed in any following studies. The problem occurs in the following situation; if an engine failure is observed between NOAP samples the oil concentrations corresponding to the time the engine of the failure will be obtained by interpolation between dates that the wear metal concentrations indicated a good engine and dates where an engine failure was indicated.

The software scan of oil concentrations is designed to alert the user of any values that fall outside a normally acceptable range. This was designed to catch values that were extrapolated without bound. However, as described earlier, that condition was eliminated. The test still is very useful in searching for possible bad data. A final scan for errors is done on the test cell date. The test cell date from the NOAP and the TEST CELL data is compared and a warning is printed if they do not match (an example can be seen in Figure 9). When the test cell dates do not match the date on the NOAP data, the NOAP data is used since it is assumed that the NOAP date and data has been corrected by the user in the manual second pass phase as described in Section 3.3.

FIGURE - 9

```
THIS IS THE 10AUG82 VERSION OF COIL TO COMBINE OIL DATA TAPES
                         NAMELIST INPUTS
IENGN  = THE LIST OF ENGINE NUMBERS CORESPONDING TO EACH PT
NVECT  = THE NUMBER OF POINTS TO BE USED IN THE DATA VECTOR
DAT    = THE LIST OF DATES CORESPOINDING TO EACH POINT
NTCTAP = THE UNIT NUMBER FOR THE TEST CELL DATA (PRESET=12)
NOATAP = THE UNIT NUMBER FOR THE OIL ANALYSIS (PRESET=13)
N3MTAP = THE UNIT NUMBER OF THE 3M DATA DRIVE (PRESET = 14)
HOLO   = THE FIRST OUTPUT HOL  (PRESET=1)
NTAP   = THE OUTPUT DRIVE NUMBER (-1 FOR NO OUTPUT)
AVGVOA = THE AVERAGE VALUES FOR TEST CELL OIL CONCENTRAT.
SPECAL = THE OPTION TO HANDLE THE SPECIAL ENGINES 777251 AND
         701252 ACCORDING TO THE AUG82 BASE (PRESET=FALSE)
&LISTO
NVECT=        590,NTCTAP=        12,NOATAP=         13,N3MTAP=         14,HOLO=  1.000000000000000    ,NTAP=          15,AVGVOA=
 0.60999995   , 0.16999996   , 0.0          , 0.0          , 0.49999997E-01, 0.28999996   , 0.28999996    ,  1.7099991    ,
  5.4599991   , 0.14999998   , 0.75999999   ,  3.1499996   ,  1.0599995    , 0.13999999   ,  2.7900000    ,  1.3699999    ,
  1.2699995   , 0.99999964E-01,SPECAL=T
&END
  16 VECTORS WERE READ FROM THE TEST CELL TAPE THE LAST  ENGINE = 777251 ON  82064.0
 *** WARNING *** FOR ENGINE 679412 THE TEST CELL DATE =82082.0 AND THE OIL TEST CELL = 82083.0
 *** WARNING *** FOR ENGINE 695024 THE TEST CELL DATE =81219.0 AND THE OIL TEST CELL = 81229.0
 *** WARNING *** FOR ENGINE 701161 THE TEST CELL DATE =81340.0 AND THE OIL TEST CELL = 81365.0
  16 VECTORS WERE READ FROM THE OIL ANALYSIS TAPE THE LAST ENGINE = 701434 ON  82107.0
  18 VECTORS WERE READ FROM THE 3M TAPE THE LAST ENGINE = 701434 ON  82061.0

WE HAVE ENTERED THE 27JUL82 VERSION OF TLKU4
 INPUT A NEGATIVE VALUE FOR J FOR ASCENDING ALTITUDES

  HOL    ENGINE          DATE          FE  AG  AL  CR  CU  MG  TI  PB  SN  NI  MO  SI  NA  BA  CD  MN  V   ZN

THIS IS THE FIRST ENTRY OF THE 4JAN79 VERSION OF DMYR - DYRMH
THIS SUBROUTINE WILL CONVERT DATES REPRESENTED BY  MONTH AND DATE TO DAY OF THE YEAR OR VISA VERSA

   1.0   687021   80260.0    9/16/80   0.6 0.2 0.0 0.0 0.1 0.3 0.3 1.8 5.5 0.2 0.8 3.2 1.1 0.1 2.8 1.4 1.3 0.1     8.7   8.7
     TEST CELL                         0.6 0.2 0.0 0.0 0.0 0.3 0.3 1.7 5.5 0.1 0.8 3.1 1.1 0.1 2.8 1.4 1.3 0.1    80259.0
     LAST OIL CHANGE                   0.6 0.2 0.0 0.0 0.0 0.3 0.3 1.7 5.5 0.1 0.8 3.1 1.1 0.1 2.8 1.4 1.3 0.1    80259.0

   2.0   687021   80261.0    9/17/80   0.6 0.2 0.0 0.0 0.1 0.3 0.3 1.8 5.5 0.2 0.8 3.2 1.0 0.1 2.7 1.3 1.3 0.1    17.3  17.3
     TEST CELL                         0.6 0.2 0.0 0.0 0.0 0.3 0.3 1.7 5.5 0.1 0.8 3.1 1.1 0.1 2.8 1.4 1.3 0.1    80259.0
     LAST OIL CHANGE                   0.6 0.2 0.0 0.0 0.0 0.3 0.3 1.7 5.5 0.1 0.8 3.1 1.1 0.1 2.8 1.4 1.3 0.1    80259.0

   3.0   687021   80262.0    9/18/80   0.7 0.2 0.0 0.0 0.1 0.3 0.3 1.9 5.6 0.2 0.8 3.2 1.0 0.1 2.7 1.3 1.2 0.1    26.0  26.0
     TEST CELL                         0.6 0.2 0.0 0.0 0.0 0.3 0.3 1.7 5.5 0.1 0.8 3.1 1.1 0.1 2.8 1.4 1.3 0.1    80259.0
     LAST OIL CHANGE                   0.6 0.2 0.0 0.0 0.0 0.3 0.3 1.7 5.5 0.1 0.8 3.1 1.1 0.1 2.8 1.4 1.3 0.1    80259.0

   4.0   687021   80263.0    9/19/80   0.7 0.2 0.0 0.0 0.1 0.3 0.3 1.9 5.6 0.2 0.8 3.2 1.0 0.1 2.7 1.3 1.2 0.1    34.7  34.7
     TEST CELL                         0.6 0.2 0.0 0.0 0.0 0.3 0.3 1.7 5.5 0.1 0.8 3.1 1.1 0.1 2.8 1.4 1.3 0.1    80259.0
     LAST OIL CHANGE                   0.6 0.2 0.0 0.0 0.0 0.3 0.3 1.7 5.5 0.1 0.8 3.1 1.1 0.1 2.8 1.4 1.3 0.1    80259.0

   5.0   687021   80264.0    9/20/80   0.7 0.2 0.0 0.0 0.1 0.4 0.4 2.0 5.6 0.2 0.8 3.2 1.0 0.1 2.7 1.3 1.2 0.1    43.4  43.4
     TEST CELL                         0.6 0.2 0.0 0.0 0.0 0.3 0.3 1.7 5.5 0.1 0.8 3.1 1.1 0.1 2.8 1.4 1.3 0.1    80259.0
     LAST OIL CHANGE                   0.6 0.2 0.0 0.0 0.0 0.3 0.3 1.7 5.5 0.1 0.8 3.1 1.1 0.1 2.8 1.4 1.3 0.1    80259.0

   6.0   687021   80265.0    9/21/80   0.7 0.2 0.0 0.0 0.1 0.4 0.4 2.0 5.7 0.2 0.8 3.2 1.0 0.1 2.7 1.3 1.2 0.1    52.0  52.0
     TEST CELL                         0.6 0.2 0.0 0.0 0.0 0.3 0.3 1.7 5.5 0.1 0.8 3.1 1.1 0.1 2.8 1.4 1.3 0.1    80259.0
     LAST OIL CHANGE                   0.6 0.2 0.0 0.0 0.0 0.3 0.3 1.7 5.5 0.1 0.8 3.1 1.1 0.1 2.8 1.4 1.3 0.1    80259.0

   7.0   687021   80266.0    9/22/80   0.7 0.2 0.0 0.0 0.1 0.4 0.4 2.1 5.7 0.2 0.8 3.2 1.0 0.1 2.6 1.3 1.2 0.1    60.7  60.7
```

4.0 DEVELOPMENT ANALYSIS AND EXPECTED PERFORMANCE OF FAILURE DETECTION PROCEDURES

This section will describe how the data vectors will be processed to derive the algorithms and other analysis tools. This will be followed by an analysis of the performance and other characteristics of the most significant algorithms which were derived during this study.

4.1 ADAPT APPROACH AND ANALYSIS TOOLS

The ADAPT approach to empirical analysis which was used to derive and test the algorithms for this study was originally developed at AVCO Corporation and called the AVCO Data Analysis and Prediction Techniques (ADAPT). This technology has been acquired, further developed and applied by the ADAPT Service Corporation. The approach has been discussed in the literature[1,2]. It is also presented in detail in Appendices A-C. However, the key components of the method will be repeated here.

The general concept of the ADAPT approach is to take the data set from the original high dimensional measurement space and transform it to a lower dimensional but optimal feature or analysis space. Unlike most pattern recognition approaches, the features are derived objectively and are the eigenvectors or optimal empirical orthogonal functions associated with the training set. Figure 10 illustrates the steps in this approach. The data vectors, constructed as described in Section 3 are represented by the schematic data vector shown in the upper left hand corner of this diagram. These data vectors are transformed into an ordered optimal coordinate system (i.e., feature space) defined by the Karhunen-Loeve expansion[3]. In addition to being objectively determined, these features are complete in the sense that before truncation all of the information in the original data space is retained. The truncation is based on analysis of the explained variation rather than the usual arbitrary rejection or selection of features.

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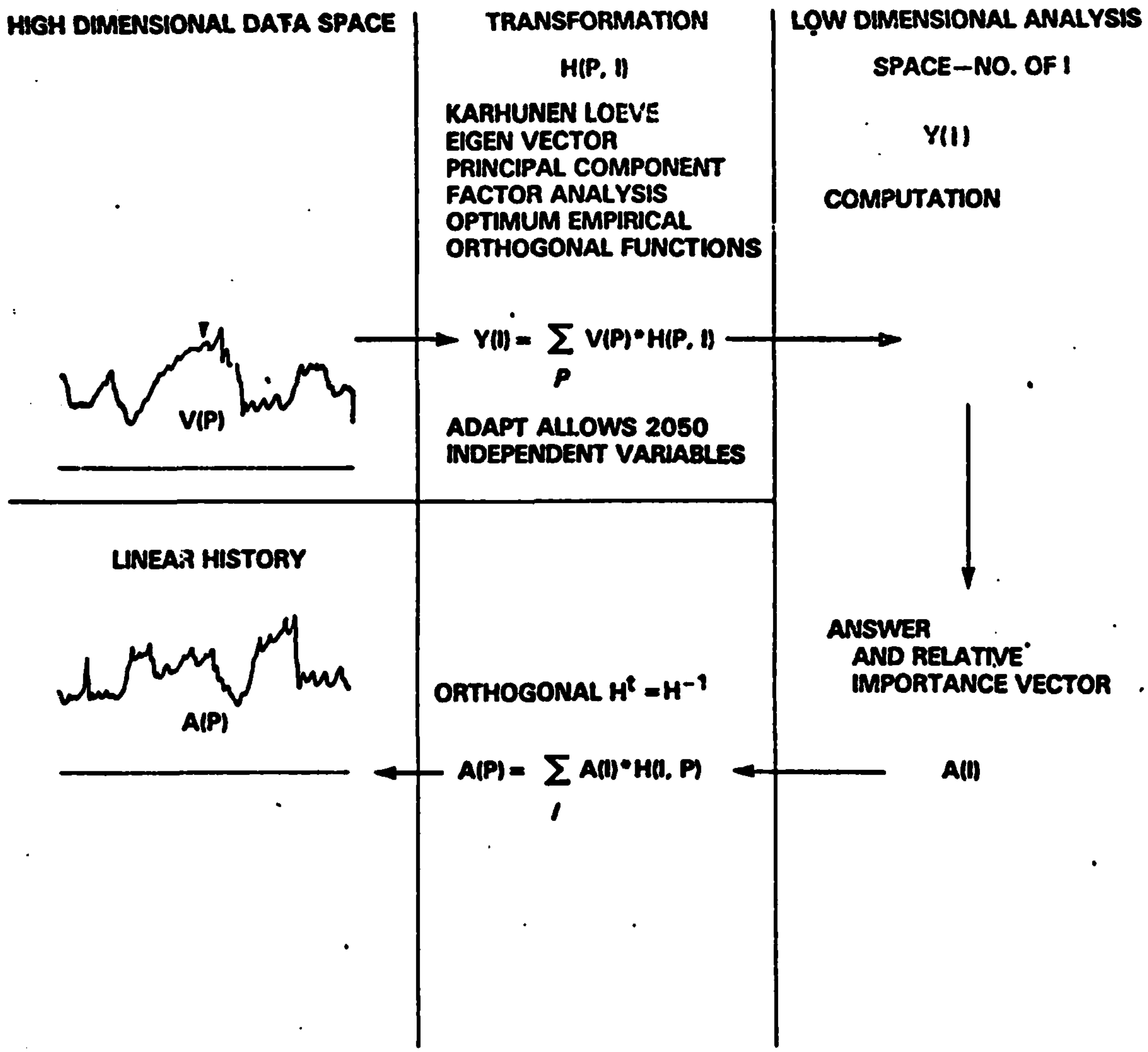
(1) Shenk, William E. et al, "The Estimation of Extratropical Cyclone Parameters", J.Appl. Meteor. 12, pp 441-451, 1973.

(2) Hunter, H.E., et al, "An Objective Method for Forecasting Tropical Cyclone Intensity Using NIMBUS 5 Electrically Scanning Microwave Radiometer", J. Appl. Meteor. 20, pp. 137-145, 1981.

(3) Andrews, H.C.; <u>Introduction to Mathematical Techniques in Pattern Recognition</u>, Wiley, 1972.

FIGURE - 10

OVERVIEW OF ADAPT ANALYSIS TECHNIQUES USED



Although the eigenvector or Karhunen-Loeve expansion are well known in the literature, there are a number of problems which have plagued the application of this technique to real data problems such as the present problem. The ADAPT approach to deriving the eigenvectors has overcomed these difficulties. A detail description of these problems and how they are overcome using the ADAPT approach to the derivation is presented in Appendix B.

The analysis and derivation of classification or regression algorithms is performed in the feature or optimal analysis space. This is indicated by the right hand side of Figure 10. Both the regression and pattern recognition algorithms are derived using the ADAPT developed independent eigenscreening approach. This approach differs from conventional screening algorithm developments in two ways: 1) the screening as performed in eigenvector space and 2) the decision as to whether a given direction should be retained or rejected is based on independent ("U" method of Lackenbrach, Mickey[4]) rather than dependent test results. This last difference is of critical importance since it can be shown that for most problems the use of dependent testing gives incorrect conclusions regarding the usefulness of a feature. Although this conclusion is generally accepted throughout the field with respect to performance estimates, it is ignored in almost all screening procedures. The details of the ADAPT independent eigenscreening approach are presented in Appendix C.

After the algorithms have been derived, they may be transformed back to the original measurement space for further analysis. This is possible since the eigenvector transformation is orthogonal and, therefore, its inverse is always known. When the algorithm has been transformed back to the original measurement space, we call it a relative importance vector because it defines the importance of each of the original variables to the decision which is being made by the algorithm.

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(4) Lackenbrach, P.A. and Mickey, M.R.; "Estimation of Error Rates in Discriminant Analysis", Technometrics, 10, pp 11-17, 1968.

Analysis Tools

This brief review of the ADAPT approach allows us to define two important analysis tools which will be made available as part of the menus if the recommended incipient failure detection demonstration system is implemented. These tools are the scatter plot projection on the significant eigendirections and the relative importance vectors associated with an unusual case. These tools would be made available to experienced analysts and would not be the primary means for defining and diagnosing incipient engine failures. The relative importance vector is defined in Appendix A. In the analysis part of the demonstration system, algorithms may be derived separating any given data vector from an ensemble of the other data vectors in the system. The relative importance vector associated with this algorithm would define which of the measurements are responsible for the unhealthy or unusual behavior associated with the engine in question.

The description of the ADAPT feature or eigenvector space points out that this is an optimal space in the sense that the greatest amount of information is presented in the minimum amount of numbers. It follows that scatter plot projections of this information on these eigendirections are ideally suited for human investigators to search for clusters. Usually, this is only justified for the dominant eigendirections which because of the nature of the eigenvector expansion are both unique and efficient in presenting the inter-relationships between the various cases. Thus, a relatively small number of two dimensional scatter plots often presents the essence of the information contained in an entire data set. By comparing the track of an engine on such a scatter plot with itself or other engines, a great deal can be learned by the experienced investigator.

In the following sub sections, we will present examples of these presentations and how they may be used by an experienced analyst to improve the diagnostics of an engine failure. However, we must emphasize all of the performances which have been given and which will be given are based on the automated algorithms and do not include any additional gain that could be obtained by an experienced analyst using these tools which will be made available. We believe that these tools will be useful in the same sense that the presentation of the raw data has been found useful in the present NOAP system.

Engine Health Eigenvector Expansion

The data vectors were prepared as described in Section 3 for the 590 observations or samples taken from the 14 engines listed in Table 2. The first column of Table 2 identifies the engine number, the second column identifies the sample or observation number and the symbol which will be used for that group of samples in the scatter plot presentation. This will be discussed later in Section 4.2. The third column presents the ID of the sample. F stands for a failure, G for a good engine and X for a questionable engine. These will also be discussed in more detail in later sections. The fourth and fifth columns describe the failure if any and present other information regarding the engines.

The eigenvector transformation used to transform the data from the measurement space to the optimal analysis or feature space was derived using 480 of the observations listed in Table 2. One hundred and ten of the observaions listed in Table 2 were not used. These 110 observations were deleted to provide a better balance between a number of observations for each of the engines used and also a better balance between good and incipient failure observations. It is important to maintain approximately equal representations of the known major divisions in constructing the eigenvector transformation if one desires that the resulting transformation represent these known variations equally.

The average of the 480 data vectors used to derive the eigenvectors was constructed. This average is presented in Figure 11. Since all of these data vectors were equalized such that each of their components have a value between one and two, the mean of each component is 1.5. Examination of Figure 11 shows that the test cell measurements have their mean approximately equal to their average. The oil measurements in general have their mean significantly lower than the average. This suggests that, in general, there are a large number of outlier cases occurring in the NOAP data. The number of outlier cases is even larger for the 3M data where the average is much smaller than the mean.

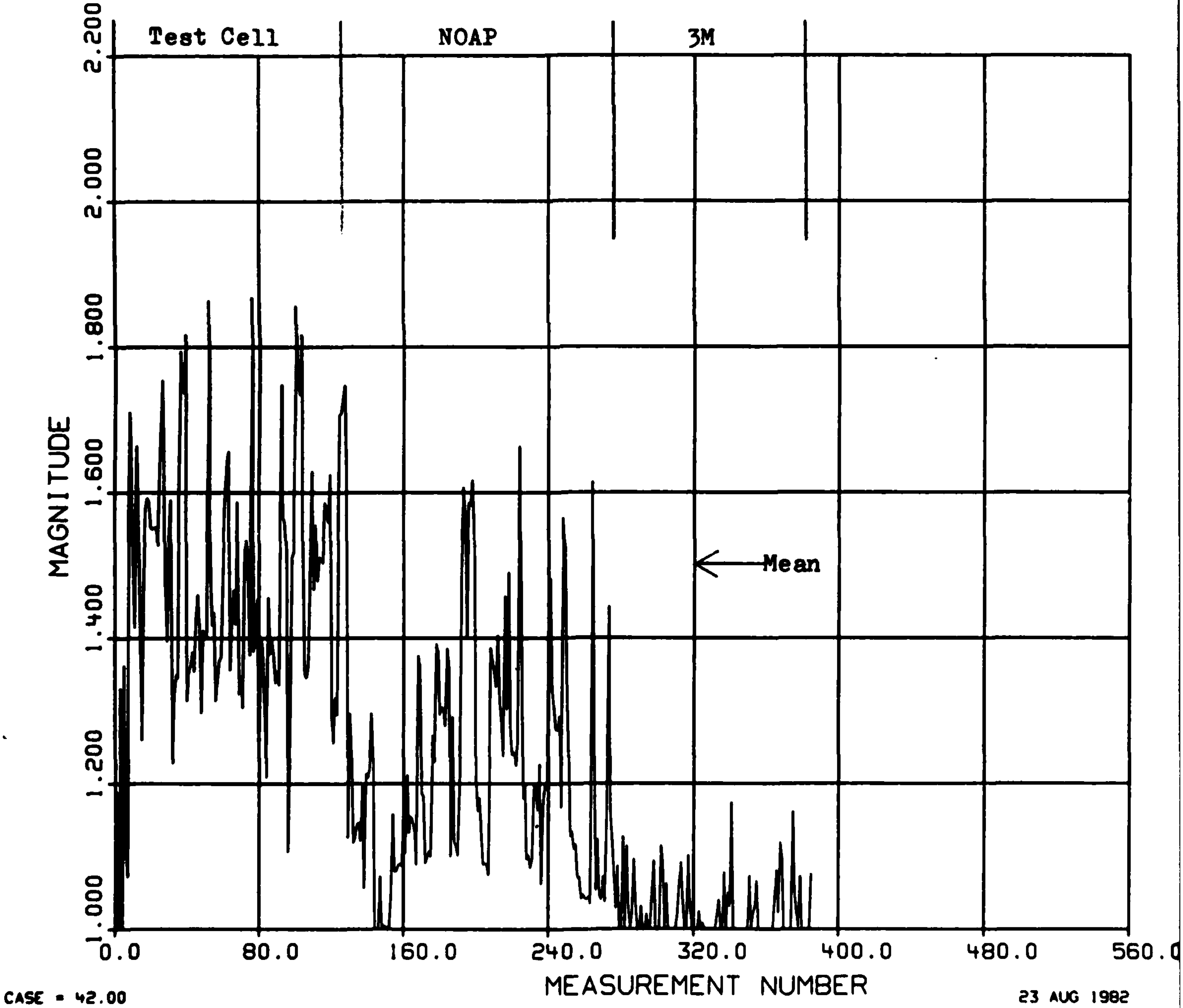
Before deriving the eigenvector transformations, the data set used to derive the eigenvectors was given a zero mean by subtracting the average data vector shown in Figure 11 for each of the data histories. This was done to all 590 observations listed in Table 2 because the zero mean data vectors would also be desired for all of the algorithm development which will follow.

TABLE 2 - SUMMARY OF CASES USED

ENG. NO.	SAMPLE NOS. (SYM)	ID	TRUTH DATA	REMARKS
687021	1-15 (Z)	X1	FUEL CONTROL FAIL @ TEST CELL	1) 1½ YR'S DATA
	16-45 (1)	G1	GOOD	
	46-60 (Y)	F1	FAN INLET CASE CRACKED, COMBUSTION CHAMBER OUTER DUCT CRACKED, BAD MAIN FUEL SPRAY PATTERN & EXCESSIVE PT7	
687279	61-70 (X)	F2	CRACKED & BENT AB FUEL PUMP	1) 3 YR's DATA
	71-80 (2)	G2		2) USED F3 FOR
	81-95 (W)	F3	CLOGGED SUMP STRAINER IN MAIN OIL PUMP	TIME TO FAIL
	96-145 (V)	F4	DIRTY (NON-METALLIC) OIL	ALGORITHM
	146-215 (3)	G3		3) F4 PICKED
	216-225 (U)	F5	MAIN FUEL SYSTEM & AB IGNITER FUEL VALVE	BY NOAP
679390	226-250 (4)	G4		
679412	251-270 (5)	G5		
695024	271-300 (T)	F6	MAIN OIL FILTER LOOSE & OUT OF ADJUSTMENT; OIL STRAINER CLOGGED	
	301-310 (S)	F7	A.B. FUEL SYSTEM FAILURE	
695195	311-330 (6)	G6		
695489	331-360 (R)	F8	ENGINE FAILED TO OPERATE & HAD OIL LEAK	
701161	361-380 (7)	G7		
701251	381-420 (8)	G8		
701251A	421-440 (Q)	X2		HYBRED CASE GOOD CELL, BAD OIL
701251B	441-460 (P)	F9	FAILED TEST CELL PERFORMANCE PASS*; AB FUEL CONTROL FAILED	*ADJUSTED TO IN 2-WEEKS
701255	461-480 (9)	G9		
701257	481-505 (O)	F10	EXCESSIVE VIBRATION	
	506-550 (N)	F11	UNKNOWN FAILURE-BASED ON RETURN FOR OVERHAUL-NO FAILURE DOCUMENTATION	
701264	551-565 (M)	F12	IGNITION SYSTEM	
701430	566-575 (A)	G10		
701434	576-590 (B)	G11		

FIGURE - 11

AVERAGE OF 480 ENGINE HEALTH MEASUREMENTS USED TO DERIVE EIGENVECTORS



The results of the ADAPT eigenvector transformation derivation program are summarized in Figure 12. This figure presents a plot of the percent of the information contained in the entire data set which is represented by each of the eigendirections or features of the optimal analysis space. This figure shows two curves. The upper curve is the cumulative sum of the lower curve. Thus, entering this figure at an abscissa value of 1, we find both the upper and lower curves have an ordinate value of approximately 25%. This indicates that the first eigendirection or feature explains approximately 25% of the variation or in more intuitive terms contains 25% of the information which was contained in the entire data set of 480 observations of 385 measurements. Entering at an abcissa value of 2, the lower curve has a value of approximately 15% and the upper curve a value of approximately 40%. This indicates that a second eigendirection contains 15% of the information in the total data set and that the first and second eigendirections taken together contain 40% of the information. Thus, if one were to plot a scatter plot of the first and second eigendirections showing each of the observations on the first and second eigendirections, this single plot would contain 40% of the information which could be obtained by examining all of 385 measurements for the 480 cases. This demonstrates the efficiency of the ADAPT scatter plots for enabling the human to observe natural clusterings of the data. Considerable additional information regarding this eigenvector expansion including plots of the more significant eigenvectors and scatter plots on a number of these eigenvectors are included in Appendix D to this report.

The scatter plot of the data on the first two eigendirections is shown in Figure 13. This figure shows considerable grouping of the cases. Much of this grouping is grouping by engine. This suggests that increasing the number of engines will provide a more complete definition of the variation and should improve the results beyond those presented in this report. The symbols used on Figure 13 are those listed in Column 2 of Table 2. The numerals and letters A and B indicate good engines and the remaining letters indicate bad engines. Thus, we see that although there is considerable grouping in these first two eigendirections, it is not predominantly good versus bad engine.

Engine Serial No. 701257 clusters in a group removed from the rest. This engine was the only engine used for which there was no 3M data and this is probably why it is separated from the rest. The two engines covering relative large regions are enclosed in solid contours. These three engines are the two engines for which data is available for

FIGURE - 12
INFORMATION (IE EXPLAINED VARIATION) AS A FUNCTION OF
DIMENSIONALITY FOR THE EIGENVECTOR REPRESENTATION OF THE ENGINE HEALTH DATA VECTOR

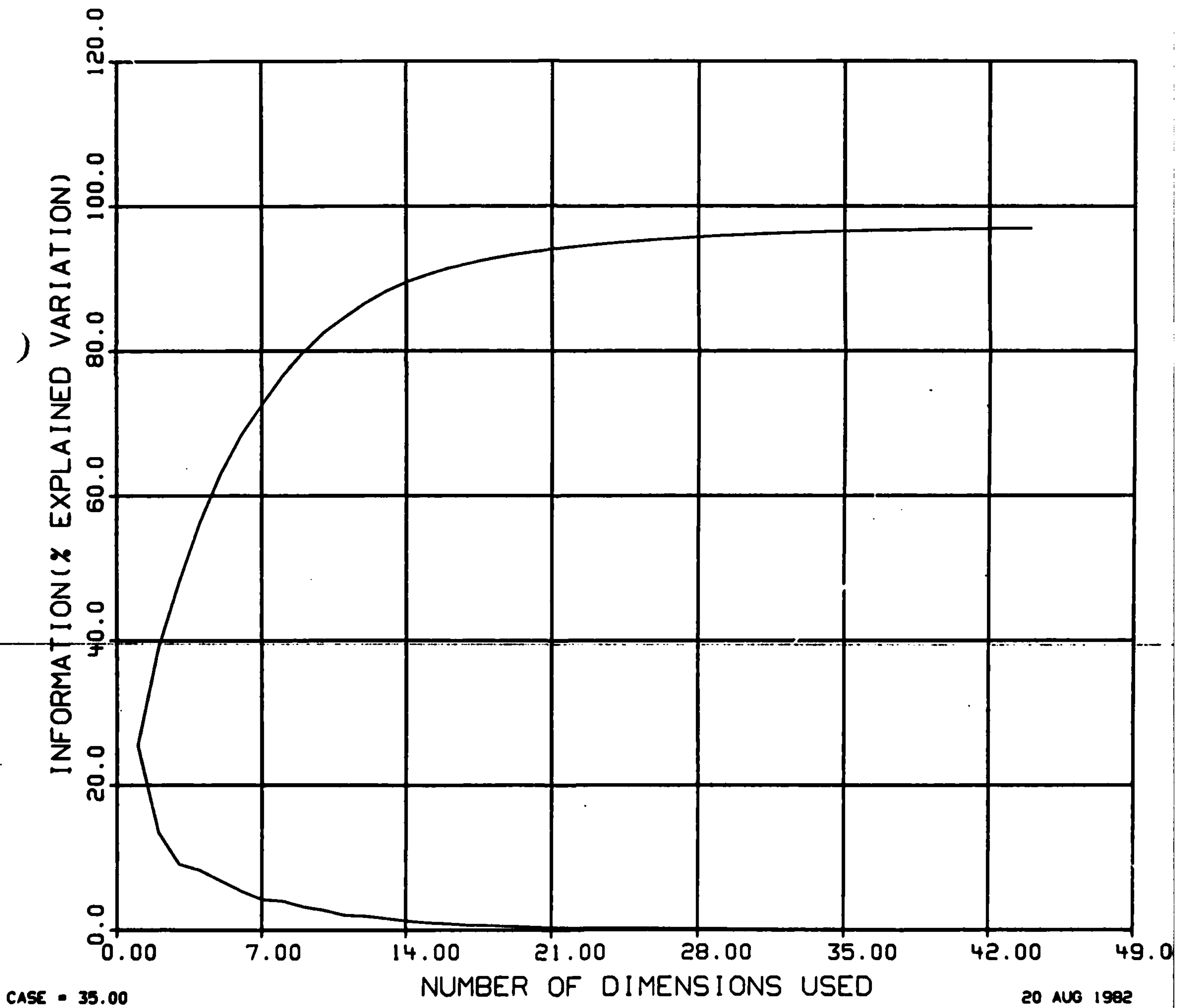
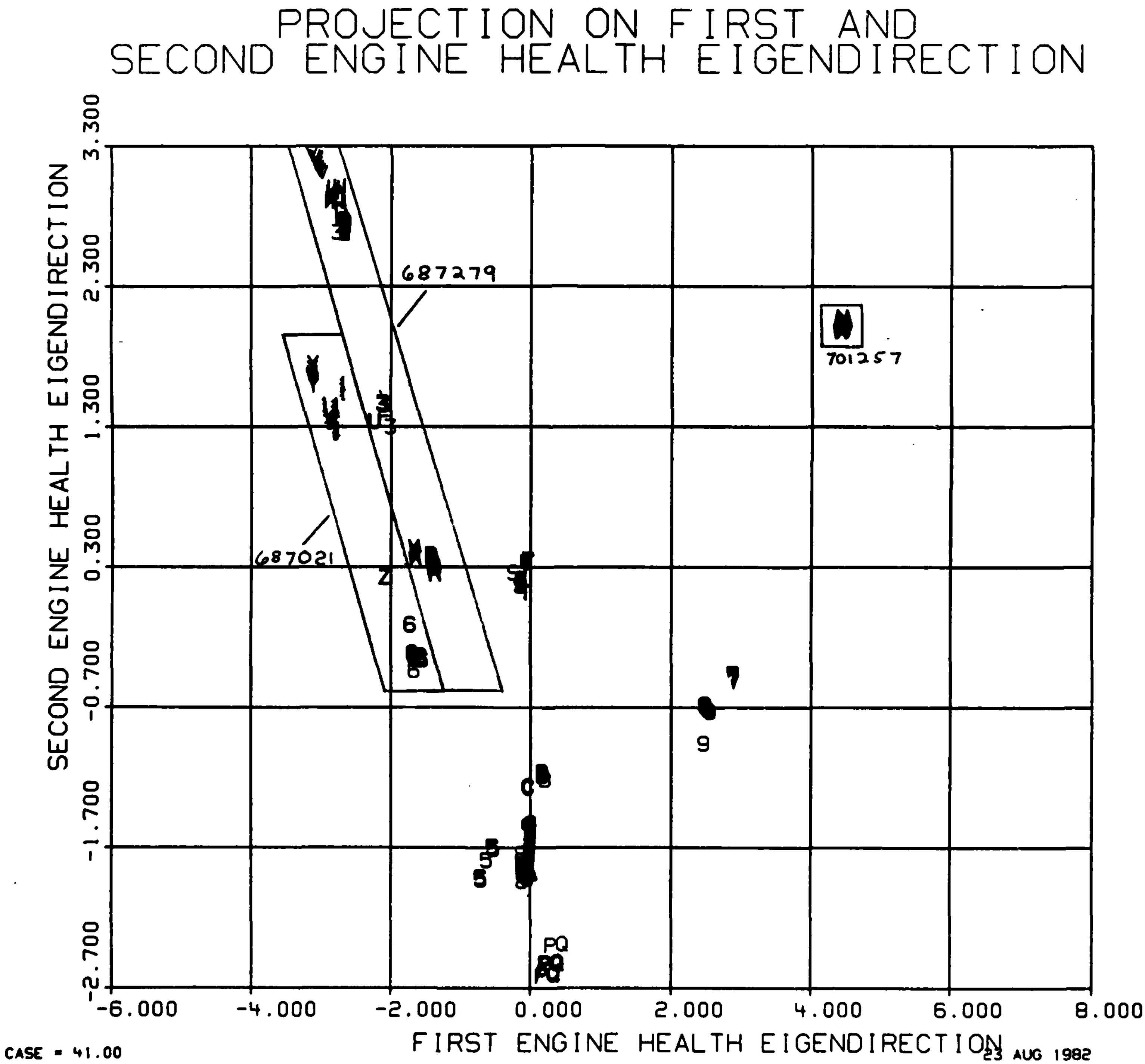


FIGURE - 13


PROJECTION ON FIRST AND
SECOND ENGINE HEALTH EIGENDIRECTION
SECOND ENGINE HEALTH EIGENDIRECTION
FIRST ENGINE HEALTH EIGENDIRECTION
3.300
2.300
1.300
0.300
-0.700
-1.700
-2.700
-6.000
-4.000
-2.000
0.000
2.000
4.000
6.000
8.000
687279
687021
701257
CASE = 41.00
23 AUG 1982

longest period of time. This suggests that if data is ilable for more engines over the entire space between two cessive overhauls, the performance of the algorithms derived m this data should improve.

DETECTION OF INCIPIENT FAILURES

This section presents information which defines in detail the rformance of the automated algorithms for detection of cipient engine failures as well as an analysis tool which n be used by an experienced analyst to further understand e health of an engine. We shall also present the relative portance vectors associated with each of the algorithms illustrate which measurements are important to the decisions.

The performance of the automated failure detection algorithms n be described either in terms of a probability of error or terms of a plot of the detection statistic for each of e 590 cases used in this study. Both the probability of ror and the detection statistics presented in this and follow- g sections are derived using the independent test method U scribed by Lackenbrach and Mickey[4].

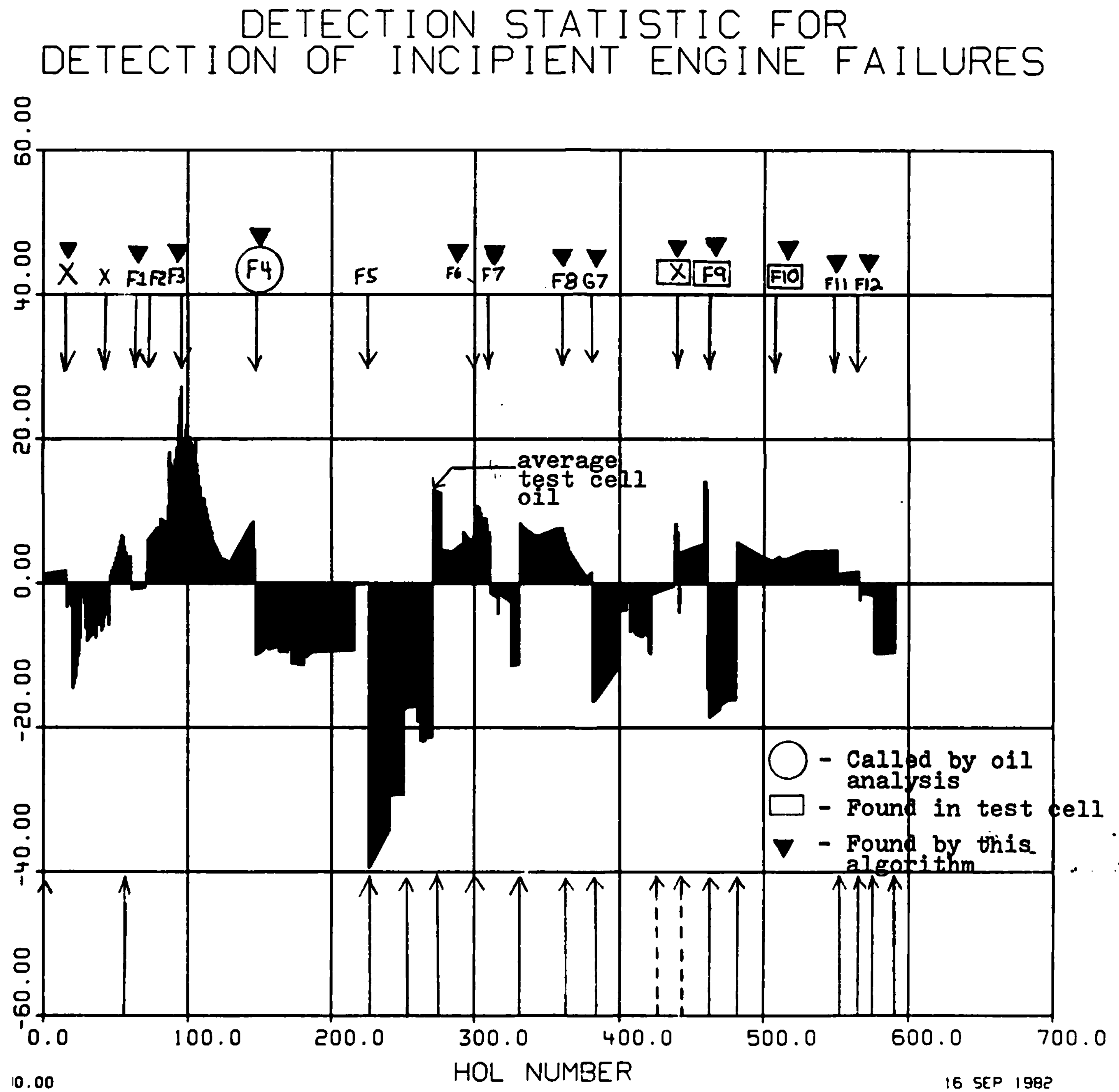
tection Algorithm Incipient Engine Failures

The first algorithm which we shall present is the algorithm r the detection of incipient engine failures. This algorithm s developed by separating those observations indicated as ilures in Table 2 from the cases indicated as good engines. e probability of error for this algorithm was 0.14. Figure presents the detection statistic for each of the 590 servations used in this study after application of this gorithm.

The detection statistic is the quantity which is calculated the algorithm and is used to decide whether a failure will cur. That is, after one calculates the detection statistic om the algorithm, it is compared with the threshold and the value exceeds the threshold, we predict that incipient ilure will occur. By setting the threshold, one may adjust e detection probability and false alarm ratio. In the velopment of the final algorithms to be used in the demonstra- on system, this will be carried out after discussions with vy personnel to insure the best trade-off between false arms and detections.

We can get a good understanding of the performance of ese algorithms simply by examining a plot of their detection atistics for each of the cases. The threshold for the plot own in Figure 14 is at a detection statistic value of 0. us, any positive detection statistic value indicates a bad gine, a negative value indicates a good engine. The ordinant

FIGURE - 14

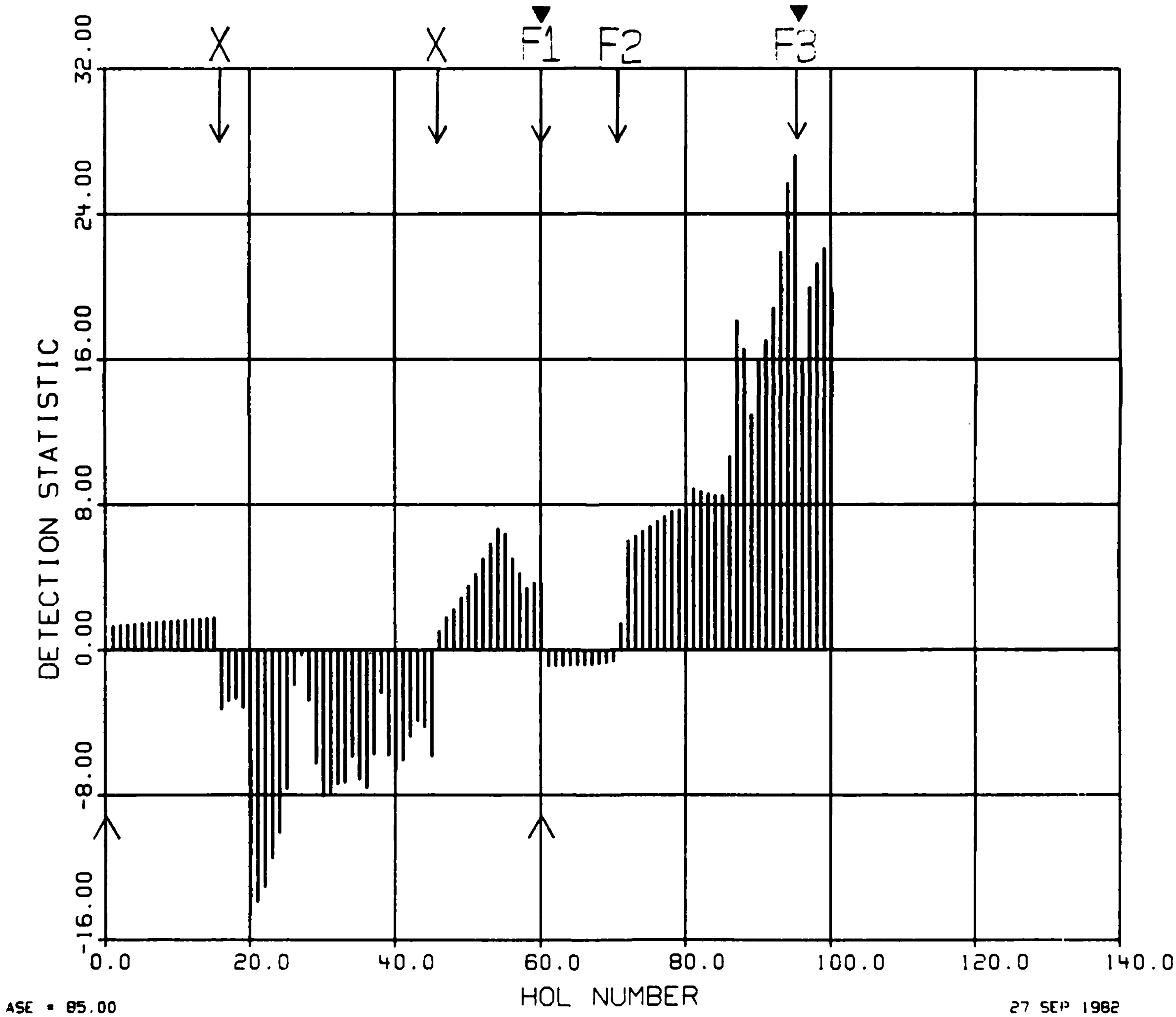

DETECTION STATISTIC FOR
DETECTION OF INCIPIENT ENGINE FAILURES
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
X
X
F1
F2
F3
F4
F5
F6
F7
F8
G7
X
F9
F10
F11
F12
average test cell oil
- Called by oil analysis
- Found in test cell
- Found by this algorithm
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
HOL NUMBER
10.00
16 SEP 1982

of Figure 14 is the detection statistic, the abscissa indicated as HOL number is the observation or sample for which the detection statistic is calculated. This plot is actually a plot of a great many individual bars. Because of the large number of cases presented in a small area, they have run together and appear as shaded area rather than as individual bars on the bar chart. Figure 15 presents a plot of the first 100 cases of Figure 14. The purpose of this presentation is to illustrate that although on Figure 14, the data looks like solid blobs, these are really made up of individual bars representing detection statistic occurring for a given observation or HOL number of the engine. In order to keep the presentation on a single sheet so that the reader may get the overall picture, we have had to allow these bars to run together, however, comparison of Figures 14 and 15 should make clear the meaning of the information presented in Figure 14 and subsequent detection statistic plots presented in this report.

To assist in the interpretation of Figure 14, two additional rows of information have been added. These are: 1) upward and 2) downward arrows indicating engines and failures, respectively. The downward facing arrows on the upper portion of this plot indicate the occurrence of each of the failures defined in Table 2. Each of these downward arrows are identified by the ID symbol and number (if applicable) shown in Table 2. Thus, the occurrence of the failures are defined by these downward pointing arrows. Those arrows for which the data preceding them at some point has positive detection statistics and, therefore, for which this algorithm would successfully identify the occurrence of the failure has been indicated by a solid downward pointing triangle above the appropriate ID. The ID included in a circle, F4, is the single case in the present data set which was called by the present operationa oil analysis. The two failure ID's, F9 and F10, enclosed in squares were the two cases called in the test cell.

In the lower half of the figure, there are a series of upward pointing arrows. These arrows indicate the beginning of the observations of a new engine. Thus, there is an upper arrow occurring at a HOL number of one which is the beginning data on the first engine. Referring to Table 2, we see that this is Engine No. 687021. The next upward pointing arrow occurs at HOL Number 61 again referring to Table 2 we see that this is the beginning of Engine 687279.

FIGURE 15 DETECTION STATISTIC FOR DETECTION OF INCIPIENT ENGINE FAILURES



Detail examination of Figure 14 in conjunction with Table 2 not only shows which failures have and have not been correctly identified, but also gives an indication of how long in advance of the failure one can first see the occurrence of the failure and how strongly it has been detected. One caution in interpreting Figure 14 is that interpolation (see Section 3.5) was used between oil samples. Thus, if a failure has occurred and been corrected and the engine does not change, the oil samples immediately following that failure are interpolations between the most recent oil sample occurring prior to the failure and the nearest oil sample after the failure. Thus, we often see a gradual slope to the right of a failure occurring within a given engine. This is due to the interpolation procedures and clearly would not occur in the real world where the algorithm would normally only be applied at the time the sampling was accomplished.

Figure 14 also shows one case identified as a failure for which a failure was not recorded in the 3M or NOAP data. This is ID number G7 on Table 2 and is also indicated by a triangle on Figure 14. Although we might attribute this to a false detection by the algorithms or an actual failure which was observed, but not recorded in the 3M system, there is some evidence that it was an incipient failure which "got well" and therefore was never observed. This evidence is the negative slope of the detection statistic. We have pointed out that negative slopes can occur after a failure because of the interpolation used for this study. However, this is only possible when the data preceding the negative slope represented a failure of the same engine. However, G7 occurred very shortly after the engine left the test cell, which in the context of this study represents the "birth of the engine" and by definition represents a healthy engine. Thus, the negative slope of G7 is <u>not</u> a result of the interpolation!

The only other explanation for a negative slope is that the engine is "getting well" as it gets older. An example of this may be oil contaminated with sufficiently large particles that the oil filter slowly removes them. In this example, the initial reading may indicate a unhealthy engine, but succeeding samples would be progressively more healthy, or the slope of the detection statistic would be negative. Thus, by the process of elimination, we believe the G7 was initially a valid case of an unhealthy engine which gradually got well and was, therefore, never discovered. Although, if it had been discovered and corrected, the engine may have lasted longer before requiring an overhaul.

Table 3 repeats the information plotted in figure 14 and 15 in tabular form. The values in table 3 are 7.5 smaller than those in the figure this adjustment of the data was made so that the seperation would be easier to see.

TABLE 3
DETECTION STATISTIC FOR DETECTION OF INCIPIENT ENGINE FAILURES
CONTINUED

HOL	DETECTION STAT	HOL	DETECTION STAT	HOL	DETECTION STAT	HOL	DETECTION STAT
201	-0.1682596E 02	202	-0.1681769E 02	203	-0.1680942E 02	204	-0.1680113E 02
205	-0.1679286E 02	206	-0.1678458E 02	207	-0.1677629E 02	208	-0.1676801E 02
209	-0.1675974E 02	210	-0.1675145E 02	211	-0.1674316E 02	212	-0.1673489E 02
213	-0.1672661E 02	214	-0.1671834E 02	215	-0.1671005E 02	216	-0.7666744E 01
217	-0.7641908E 01	218	-0.7617068E 01	219	-0.7592230E 01	220	-0.7567390E 01
221	-0.7542549E 01	222	-0.7517712E 01	223	-0.7492872E 01	224	-0.7468034E 01
225	-0.7443193E 01	226	-0.4687210E 02	227	-0.4663866E 02	228	-0.4626398E 02
229	-0.4588925E 02	230	-0.4551456E 02	231	-0.4513986E 02	232	-0.4476517E 02
233	-0.4439049E 02	234	-0.4401575E 02	235	-0.4364107E 02	236	-0.4326639E 02
237	-0.4289169E 02	238	-0.4251700E 02	239	-0.4214226E 02	240	-0.4176764E 02
241	-0.3682193E 02	242	-0.3678900E 02	243	-0.3675613E 02	244	-0.3672321E 02
245	-0.3669029E 02	246	-0.3665736E 02	247	-0.3667575E 02	248	-0.3669415E 02
249	-0.3671257E 02	250	-0.3673105E 02	251	-0.2482631E 02	252	-0.2470175E 02
253	-0.2457710E 02	254	-0.2455621E 02	255	-0.2453532E 02	256	-0.2451443E 02
257	-0.2449353E 02	258	-0.2447266E 02	259	-0.2445175E 02	260	-0.2655743E 02
261	-0.2659567E 02	262	-0.2918416E 02	263	-0.2925125E 02	264	-0.2931828E 02
265	-0.2927513E 02	266	-0.2872351E 02	267	-0.2883139E 02	268	-0.2880714E 02
269	-0.2878296E 02	270	-0.2875874E 02	271	0.5569159E 01	272	0.5486553E 01
273	0.5403949E 01	274	0.5321344E 01	275	0.5238733E 01	276	0.5156122E 01
277	-0.2740580E 01	278	-0.2779077E 01	279	-0.2817589E 01	280	-0.2856088E 01
281	-0.2894591E 01	282	-0.2933111E 01	283	-0.2971612E 01	284	-0.3010115E 01
285	-0.2843789E 01	286	-0.2676909E 01	287	-0.2510048E 01	288	-0.2343162E 01
289	-0.2176266E 01	290	-0.2066618E 01	291	-0.1966812E 01	292	-0.2649164E 00
293	-0.5278635E 00	294	-0.7897702E 00	295	-0.1051687E 01	296	-0.1313611E 01
297	-0.1603148E 01	298	-0.1246010E 01	299	-0.7768197E 00	300	-0.3699543E 00
301	0.3303407E 01	302	0.3319881E 01	303	0.3058112E 01	304	0.2378197E 01
305	0.1698288E 01	306	0.1661471E 01	307	0.1624660E 01	308	0.1587843E 01
309	-0.2485247E 00	310	-0.2853956E 00	311	-0.8772315E 01	312	-0.8918595E 01
313	-0.9064890E 01	314	-0.9211164E 01	315	-0.9357464E 01	316	-0.1166625E 02
317	-0.8872767E 01	318	-0.9035929E 01	319	-0.9182246E 01	320	-0.9328544E 01
321	-0.9474847E 01	322	-0.9621119E 01	323	-0.9767396E 01	324	-0.9913679E 01
325	-0.1891789E 02	326	-0.1886919E 02	327	-0.1882047E 02	328	-0.1877180E 02
329	-0.1872310E 02	330	-0.1867441E 02	331	0.9987539E 00	332	0.7441160E 00
333	0.5154556E 00	334	0.3514962E 00	335	0.1875469E 00	336	0.2359319E-01
337	-0.1403463E 00	338	-0.3042976E 00	339	-0.4682544E 00	340	-0.6321981E 00
341	-0.6813905E 00	342	-0.7141770E 00	343	-0.7469618E 00	344	-0.7236212E 00
345	-0.6441395E 00	346	-0.5646822E 00	347	-0.4852016E 00	348	-0.4057366E 00
349	-0.3262650E 00	350	-0.2467876E 00	351	-0.1673035E 00	352	-0.8783031E-01
353	-0.8354366E-02	354	0.7113677E-01	355	0.1568396E 00	356	0.2449160E 00
357	0.2636824E 00	358	0.2824440E 00	359	0.3012075E 00	360	0.3199749E 00
361	-0.4209054E 00	362	-0.1068998E 01	363	-0.1717080E 01	364	-0.2365159E 01
365	-0.3013947E 01	366	-0.3308489E 01	367	-0.3603130E 01	368	-0.3897780E 01
369	-0.4192301E 01	370	-0.4486950E 01	371	-0.4781600E 01	372	-0.5076128E 01
373	-0.5370766E 01	374	-0.5665446E 01	375	-0.5960039E 01	376	-0.6254820E 01
377	-0.6392705E 01	378	-0.6212405E 01	379	-0.6032071E 01	380	-0.5851728E 01
381	-0.2377878E 02	382	-0.2370918E 02	383	-0.2365236E 02	384	-0.2338385E 02
385	-0.2309483E 02	386	-0.2280580E 02	387	-0.2251677E 02	388	-0.2222775E 02
389	-0.2193874E 02	390	-0.2164970E 02	391	-0.2136067E 02	392	-0.2107161E 02
393	-0.2078261E 02	394	-0.2049359E 02	395	-0.2020454E 02	396	-0.1991550E 02
397	-0.1962650E 02	398	-0.1077949E 02	399	-0.1049050E 02	400	-0.1118836E 02

TABLE 3

DETECTION STATISTIC FOR DETECTION OF INCIPIENT ENGINE FAILURES

HOL	DETECTION STAT	HOL	DETECTION STAT	HOL	DETECTION STAT	HOL	DETECTION STAT
1	-0.6075038E 01	2	-0.6037438E 01	3	-0.5999715E 01	4	-0.5961075E 01
5	-0.5922445E 01	6	-0.5886152E 01	7	-0.5857450E 01	8	-0.5828748E 01
9	-0.5798736E 01	10	-0.5766377E 01	11	-0.5733990E 01	12	-0.5701629E 01
13	-0.5669241E 01	14	-0.5636859E 01	15	-0.5604485E 01	16	-0.1070250E 02
17	-0.1022254E 02	18	-0.1010676E 02	19	-0.1058957E 02	20	-0.2199187E 02
21	-0.2131833E 02	22	-0.2049136E 02	23	-0.1889995E 02	24	-0.1749225E 02
25	-0.1508053E 02	26	-0.9322161E 01	27	-0.7697547E 01	28	-0.1020233E 02
29	-0.1366513E 02	30	-0.1547319E 02	31	-0.1525981E 02	32	-0.1480079E 02
33	-0.1471607E 02	34	-0.1329718E 02	35	-0.1455011E 02	36	-0.1501979E 02
37	-0.1316225E 02	38	-0.9767459E 01	39	-0.1323039E 02	40	-0.1404854E 02
41	-0.1347499E 02	42	-0.1217612E 02	43	-0.1129834E 02	44	-0.1166482E 02
45	-0.1326563E 02	46	-0.6356075E 01	47	-0.5604072E 01	48	-0.5161559E 01
49	-0.4516901E 01	50	-0.3872260E 01	51	-0.3215178E 01	52	-0.2380704E 01
53	-0.1546221E 01	54	-0.7117445E 00	55	-0.1000358E 01	56	-0.2373418E 01
57	-0.3185608E 01	58	-0.3997791E 01	59	-0.3702036E 01	60	-0.3691925E 01
61	-0.8282899E 01	62	-0.8274519E 01	63	-0.8266126E 01	64	-0.8256349E 01
65	-0.8240193E 01	66	-0.8224023E 01	67	-0.8207871E 01	68	-0.8151897E 01
69	-0.8093130E 01	70	-0.8034355E 01	71	-0.5937922E 01	72	-0.1387919E 01
73	-0.1117361E 01	74	-0.8467951E 00	75	-0.5762320E 00	76	-0.3056574E 00
77	-0.3508854E-01	78	0.2355556E 00	79	0.3148680E 00	80	0.3941793E 00
81	0.1490821E 01	82	0.1335173E 01	83	0.1216483E 01	84	0.1113727E 01
85	0.1097622E 01	86	0.3258515E 01	87	0.1072967E 02	88	0.9177131E 01
89	0.5553464E 01	90	0.8468244E 01	91	0.9639341E 01	92	0.1142081E 02
93	0.1448270E 02	94	0.1828297E 02	95	0.1982681E 02	96	0.8542032E 01
97	0.1253979E 02	98	0.1387488E 02	99	0.1470341E 02	100	0.1243936E 02
101	0.1282747E 02	102	0.1206238E 02	103	0.1092713E 02	104	0.1167147E 02
105	0.1263480E 02	106	0.9095583E 01	107	0.7485351E 01	108	0.5875163E 01
109	0.4410972E 01	110	0.4352814E 01	111	0.4211942E 01	112	0.3002364E 01
113	0.2122931E 01	114	0.1243500E 01	115	0.3640059E 00	116	-0.2723622E 00
117	-0.1488571E 01	118	-0.1940299E 01	119	-0.2354864E 01	120	-0.2769429E 01
121	-0.3184000E 01	122	-0.3598581E 01	123	-0.3966593E 01	124	-0.4055186E 01
125	-0.4143789E 01	126	-0.4232385E 01	127	-0.4320971E 01	128	-0.4467684E 01
129	-0.4311930E 01	130	-0.3954283E 01	131	-0.3596658E 01	132	-0.3239027E 01
133	-0.2881365E 01	134	-0.2523740E 01	135	-0.2166099E 01	136	-0.1808452E 01
137	-0.1450823E 01	138	-0.1093201E 01	139	-0.7355683E 00	140	-0.3779203E 00
141	-0.2028555E-01	142	0.3373380E 00	143	0.6949956E 00	144	0.8875434E 00
145	0.1161077E 01	146	-0.2743499E 01	147	-0.1733972E 02	148	-0.1723441E 02
149	-0.1712912E 02	150	-0.1702380E 02	151	-0.1689340E 02	152	-0.1675047E 02
153	-0.1642023E 02	154	-0.1571519E 02	155	-0.1637006E 02	156	-0.1660262E 02
157	-0.1652632E 02	158	-0.1645004E 02	159	-0.1639149E 02	160	-0.1636847E 02
161	-0.1634544E 02	162	-0.1538455E 02	163	-0.1676987E 02	164	-0.1694954E 02
165	-0.1690974E 02	166	-0.1686995E 02	167	-0.1683014E 02	168	-0.1690089E 02
169	-0.1697166E 02	170	-0.1602779E 02	171	-0.1654175E 02	172	-0.1849149E 02
173	-0.1852353E 02	174	-0.1855548E 02	175	-0.1858746E 02	176	-0.1861943E 02
177	-0.1865141E 02	178	-0.1868338E 02	179	-0.1871535E 02	180	-0.1874731E 02
181	-0.1695697E 02	182	-0.1763728E 02	183	-0.1746552E 02	184	-0.1729373E 02
185	-0.1712198E 02	186	-0.1695016E 02	187	-0.1694189E 02	188	-0.1693361E 02
189	-0.1692532E 02	190	-0.1691704E 02	191	-0.1690877E 02	192	-0.1690048E 02
193	-0.1689220E 02	194	-0.1688391E 02	195	-0.1687566E 02	196	-0.1686737E 02
197	-0.1685910E 02	198	-0.1685080E 02	199	-0.1684253E 02	200	-0.1683424E 02

TABLE 3
DETECTION STATISTIC FOR DETECTION OF INCIPIENT ENGINE FAILURES
CONTINUED

HOL	DETECTION STAT	HOL	DETECTION STAT	HOL	DETECTION STAT	HOL	DETECTION STAT
401	-0.1116935E 02	402	-0.1115034E 02	403	-0.1113132E 02	404	-0.1111229E 02
405	-0.9459343E 01	406	-0.9440324E 01	407	-0.1406404E 02	408	-0.1382692E 02
409	-0.1385412E 02	410	-0.1415839E 02	411	-0.1446269E 02	412	-0.1453500E 02
413	-0.1464174E 02	414	-0.1474848E 02	415	-0.1483257E 02	416	-0.1464467E 02
417	-0.1429339E 02	418	-0.1449855E 02	419	-0.1470986E 02	420	-0.1697525E 02
421	-0.1723293E 02	422	-0.8888253E 01	423	-0.8815800E 01	424	-0.8743351E 01
425	-0.8670897E 01	426	-0.8598462E 01	427	-0.8526005E 01	428	-0.8453561E 01
429	-0.8381105E 01	430	-0.8308662E 01	431	-0.8236202E 01	432	-0.8163757E 01
433	-0.8091311E 01	434	-0.8018870E 01	435	-0.7946420E 01	436	-0.7873969E 01
437	-0.7801521E 01	438	0.8289516E 00	439	0.9014019E 00	440	-0.2564211E 00
441	-0.1143589E 02	442	-0.3019248E 01	443	-0.2946792E 01	444	-0.2874346E 01
445	-0.2801900E 01	446	-0.2729461E 01	447	-0.2657001E 01	448	-0.2584563E 01
449	-0.2512121E 01	450	-0.2439681E 01	451	-0.2367223E 01	452	-0.2294783E 01
453	-0.2222334E 01	454	-0.2149894E 01	455	-0.2077453E 01	456	-0.2005014E 01
457	-0.1932574E 01	458	0.6697780E 01	459	0.6770112E 01	460	0.5612514E 01
461	-0.2207393E 02	462	-0.2601007E 02	463	-0.2585408E 02	464	-0.2569807E 02
465	-0.2554205E 02	466	-0.2538600E 02	467	-0.2522997E 02	468	-0.2507396E 02
469	-0.2491792E 02	470	-0.2427821E 02	471	-0.2413689E 02	472	-0.2399551E 02
473	-0.2385416E 02	474	-0.2371281E 02	475	-0.2365108E 02	476	-0.2362917E 02
477	-0.2360727E 02	478	-0.2358534E 02	479	-0.2356349E 02	480	-0.2354152E 02
481	-0.1650379E 01	482	-0.1766037E 01	483	-0.1881156E 01	484	-0.1996813E 01
485	-0.2111933E 01	486	-0.2227591E 01	487	-0.2342706E 01	488	-0.2458366E 01
489	-0.2574018E 01	490	-0.2689136E 01	491	-0.2804790E 01	492	-0.2919908E 01
493	-0.3035561E 01	494	-0.3150682E 01	495	-0.3266336E 01	496	-0.3381452E 01
497	-0.3497104E 01	498	-0.3612759E 01	499	-0.3694283E 01	500	-0.3776469E 01
501	-0.3858655E 01	502	-0.3940907E 01	503	-0.4023097E 01	504	-0.4105284E 01
505	-0.4187531E 01	506	-0.4168132E 01	507	-0.4032588E 01	508	-0.3897030E 01
509	-0.3761486E 01	510	-0.3625919E 01	511	-0.3957409E 01	512	-0.3959044E 01
513	-0.3960689E 01	514	-0.3962317E 01	515	-0.3963974E 01	516	-0.3914677E 01
517	-0.3831402E 01	518	-0.3748123E 01	519	-0.3664834E 01	520	-0.3581556E 01
521	-0.3498280E 01	522	-0.3415006E 01	523	-0.3331738E 01	524	-0.3248462E 01
525	-0.3165185E 01	526	-0.3081906E 01	527	-0.2998629E 01	528	-0.2915336E 01
529	-0.2910077E 01	530	-0.2904152E 01	531	-0.2898230E 01	532	-0.2892300E 01
533	-0.2886378E 01	534	-0.2880454E 01	535	-0.2874537E 01	536	-0.2868608E 01
537	-0.2862686E 01	538	-0.2856759E 01	539	-0.2850841E 01	540	-0.2844913E 01
541	-0.2838989E 01	542	-0.2833064E 01	543	-0.2827139E 01	544	-0.2821212E 01
545	-0.2815291E 01	546	-0.2809366E 01	547	-0.2803442E 01	548	-0.2797520E 01
549	-0.2791595E 01	550	-0.2785671E 01	551	-0.6041701E 01	552	-0.6017377E 01
553	-0.5993045E 01	554	-0.5968723E 01	555	-0.5944400E 01	556	-0.5920074E 01
557	-0.5895751E 01	558	-0.5871424E 01	559	-0.5848717E 01	560	-0.5826615E 01
561	-0.5804512E 01	562	-0.5782413E 01	563	-0.5760317E 01	564	-0.5738214E 01
565	-0.5716110E 01	566	-0.9731809E 01	567	-0.8806905E 01	568	-0.8820228E 01
569	-0.8833549E 01	570	-0.8846880E 01	571	-0.8860196E 01	572	-0.8919337E 01
573	-0.8989841E 01	574	-0.9060380E 01	575	-0.9130865E 01	576	-0.1701540E 02
577	-0.1711795E 02	578	-0.1722049E 02	579	-0.1720274E 02	580	-0.1718234E 02
581	-0.1716194E 02	582	-0.1714156E 02	583	-0.1712112E 02	584	-0.1710074E 02
585	-0.1708034E 02	586	-0.1705995E 02	587	-0.1703954E 02	588	-0.1701912E 02
589	-0.1699873E 02	590	-0.1697832E 02				

Figure 16 presents the relative importance vector associated with the algorithm used to calculate the detection statistics presented in Figure 14 and Table 3. This figure plots each of the 385 measurements listed in Table 2 and their relative importance for incipient engine failures. We have also indicated by arrows and call outs some of the more important contributors to this decision. Notice, that the oil analysis presents the most significant information used for this diagnosis although the test cell is also very important and some importance is associated with some of the 3M measurements. Detail analysis of the important wear metal concentrations shows the measurements taken a few hours before the failure are more important than those immediately prior to the failure. This is an artifact which is also due to the interpolation discussed above. Since this artifact will not be present in the real world application we can also expect improvement in performance due to this effect.

The measurement number shown along the abscissa is the same measurement number identified in Table 1. The magnitude is a relative magnitude and it is the absolute value of this magnitude which determines the importance. Thus, a measurement having a value of minus 2 is equally important to a measurement having a value of plus 2. For further discussion

of the relative vector, the reader is referred to References (1), (2) and to Appendix A. To further assist in identifying the measurements, the information presented in Figure 16 is repeated in Table 4, where each relative importance is preceded by an interger identifying the measurement. This measurement identifying interger can be used to relate the measurement number (also shown as the abscissa on Figure 16) to the measurement name given in Table 1.

FIGURE - 16

RELATIVE IMPORTANCE VECTOR FOR INCIPIENT ENGINE FAILURE DETECTION ALGORITHM (590 CASE STUDY)

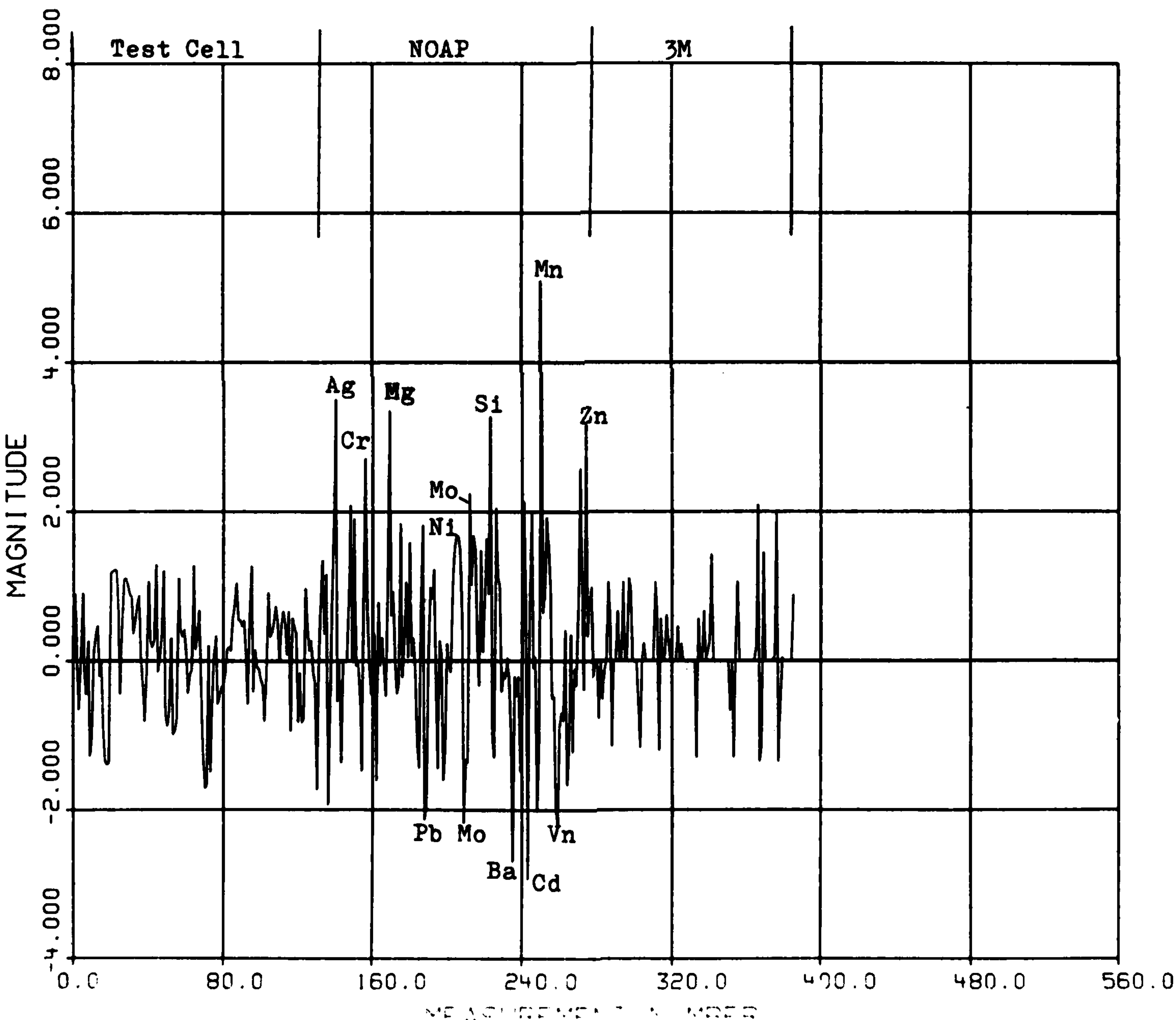


TABLE 4

RELATIVE IMPORTANCE OF EACH MEASUREMENT FOR DETECTING ENGINE FAILURES

MEAS	REL. IMPORTANCE	MEAS	REL. IMPORTANCE	MEAS	REL. IMPORTANCE	MEAS	REL. IMPORTANCE
1	0.8934487E 00	2	0.0	3	-0.6498448E 00	4	0.0
5	0.9099075E 00	6	-0.1717615E 00	7	-0.4472955E 00	8	0.2634745E 00
9	-0.1277394E 01	10	-0.9848390E 00	11	0.1086377E 00	12	0.3694587E 00
13	0.4732450E 00	14	-0.2053033E 00	15	0.7714164E-02	16	-0.9216449E 00
17	-0.1347072E 01	18	-0.1388880E 01	19	-0.1373728E 01	20	0.1170446E 01
21	0.1202013E 01	22	0.1220170E 01	23	0.1208627E 01	24	0.6374776E 00
25	-0.4463237E 00	26	0.4577616E 00	27	0.1093096E 01	28	0.1107224E 01
29	0.1019790E 01	30	0.9018096E 00	31	0.8454996E 00	32	0.3635876E 00
33	0.5398641E 00	34	0.7600539E 00	35	0.8749651E 00	36	0.2965026E-01
37	-0.3269640E 00	38	-0.8094662E 00	39	-0.1786201E 00	40	0.1069321E 01
41	0.2731076E 00	42	0.1810486E 00	43	0.2656019E 00	44	0.1285028E 01
45	-0.1489392E 00	46	0.4787353E-01	47	0.3277532E 00	48	0.1206516E 01
49	-0.7207189E 00	50	-0.8740205E 00	51	-0.6678639E 00	52	0.3049996E 00
53	-0.9890826E 00	54	-0.9450681E 00	55	-0.7808443E 00	56	0.1108752E 01
57	0.4163638E 00	58	0.3261063E 00	59	0.4185230E 00	60	0.8595651E-01
61	-0.4304591E 00	62	-0.1812835E 00	63	-0.1204229E 00	64	0.1276188E 01
65	0.1562604E 00	66	0.3313220E 00	67	0.6770234E 00	68	-0.2969453E 00
69	-0.1200371E 01	70	-0.1712771E 01	71	-0.1685382E 01	72	0.2067771E 00
73	-0.1492722E 01	74	-0.5618961E 00	75	0.9233391E-01	76	0.3375543E 00
77	-0.5767193E 00	78	-0.4696499E 00	79	-0.3460153E 00	80	-0.3282860E 00
81	-0.1955249E 00	82	0.1595036E 00	83	0.1886366E 00	84	0.1345268E 00
85	0.5871367E 00	86	0.7537163E 00	87	0.1044842E 01	88	0.5486360E 00
89	0.5457790E 00	90	0.4651310E 00	91	0.5464313E 00	92	0.1123170E 00
93	-0.5767986E 00	94	0.5556448E 00	95	0.1270509E 01	96	-0.4132727E 00
97	0.1500224E 00	98	-0.8528614E-01	99	-0.1073871E 00	100	-0.2450196E 00
101	-0.3136359E 00	102	-0.8042147E 00	103	-0.1770408E 00	104	0.9142579E 00
105	0.3247203E 00	106	0.3814529E 00	107	0.5206566E 00	108	0.7337209E 00
109	0.5267778E 00	110	0.5212370E-02	111	0.4746042E 00	112	0.6676615E 00
113	0.4959108E 00	114	0.8788270E-01	115	0.6595090E 00	116	-0.9385188E 00
117	0.5753794E 00	118	0.4473507E 00	119	0.3659686E 00	120	-0.8192980E 00
121	-0.1611876E 00	122	-0.8273473E 00	123	-0.7775759E 00	124	0.9729446E 00
125	0.4732988E 00	126	0.1361156E 00	127	0.2719671E 00	128	-0.1532264E 00
129	-0.2840513E 00	130	-0.1730958E 01	131	-0.2909893E-01	132	0.8146527E 00
133	0.1345251E 01	134	0.3652986E 00	135	0.1159966E 01	136	-0.1934310E 01
137	-0.7559242E 00	138	0.7424133E 00	139	0.1657385E 01	140	0.3500538E 01
141	-0.5431552E 00	142	-0.3004225E-01	143	-0.1362413E 01	144	0.0
145	0.0	146	0.0	147	0.7463484E 00	148	0.2084712E 01
149	-0.8832578E-02	150	0.1900508E 01	151	-0.6280541E-01	152	0.0
153	-0.4027243E 00	154	-0.1474711E 01	155	0.7919631E 00	156	0.2710629E 01
157	0.6989303E 00	158	-0.3300804E-01	159	-0.4526460E 00	160	0.3991086E 00
161	0.3402334E 00	162	-0.1602596E 01	163	0.7855083E 00	164	-0.6135349E-01
165	0.3132734E 00	166	-0.1110028E 00	167	-0.4718794E 00	168	0.8529196E 00
169	0.3351340E 01	170	0.6099386E 00	171	0.9267356E 00	172	0.1996185E-01
173	-0.4402370E 00	174	-0.3176594E 00	175	0.1838892E 01	176	-0.2184756E 00
177	0.2848958E 00	178	0.1058579E 01	179	0.5150238E-01	180	0.1582587E 01
181	0.6824994E-01	182	0.3047652E 00	183	-0.2627738E 00	184	-0.1147137E 01
185	-0.1435264E 01	186	0.7971256E 00	187	0.1818869E 01	188	-0.2132401E 01
189	-0.1972976E 01	190	0.2533190E-01	191	0.9874731E 00	192	0.8319280E 00
193	0.1224737E 01	194	-0.1796666E 00	195	-0.1440755E 01	196	0.2690501E 00
197	0.9372038E-01	198	-0.1600819E 01	199	-0.1218620E 01	200	0.2340994E 00

TABLE 4
RELATIVE IMPORTANCE OF EACH MEASUREMENT FOR DETECTING ENGINE FAILURES
CONTINUED

MEAS	REL. IMPORTANCE	MEAS	REL. IMPORTANCE	MEAS	REL. IMPORTANCE	MEAS	REL. IMPORTANCE
201	-0.3371549E-01	202	-0.1533018E 00	203	0.9925084E 00	204	0.1502901E 01
205	0.1678898E 01	206	0.1671430E 01	207	0.1473691E 01	208	0.5771832E 00
209	-0.2173101E 01	210	-0.1318635E 01	211	-0.1366706E 01	212	0.2240350E 01
213	0.1016667E 01	214	0.1680344E 01	215	0.1515994E 01	216	0.1769063E 00
217	-0.3302565E 00	218	0.1476984E 01	219	0.1206017E 00	220	0.7947659E 00
221	0.1641100E 01	222	0.9001307E 00	223	0.3271212E 01	224	-0.9850897E 00
225	-0.1294182E 01	226	0.2048883E 01	227	0.1123338E 01	228	0.9859306E 00
229	-0.4109336E 00	230	-0.1596781E 00	231	-0.2385519E 00	232	0.4354818E-01
233	-0.2577906E 00	234	-0.9575542E 00	235	-0.2692174E 01	236	-0.2107765E 00
237	-0.4705226E 00	238	-0.2111285E 00	239	-0.1482300E 01	240	-0.5173110E 00
241	0.2136491E 01	242	0.7269270E 00	243	-0.2928626E 01	244	0.7575279E 00
245	0.1977688E 01	246	-0.9731436E-01	247	0.5649849E-01	248	-0.2019858E 01
249	-0.1217217E 01	250	0.5090673E 01	251	0.6460260E 00	252	0.8938382E 00
253	0.1923118E 01	254	0.1570183E 01	255	0.9461408E 00	256	-0.5045853E 00
257	-0.4783190E 00	258	-0.2016536E 01	259	-0.2231807E 01	260	-0.8800841E 00
261	-0.6929082E 00	262	-0.8039590E 00	263	0.4108495E 00	264	-0.1664844E 01
265	-0.1244748E 01	266	0.3525545E 00	267	-0.1224033E 01	268	-0.1053982E 00
269	-0.3338456E 00	270	0.8495033E 00	271	0.2577494E 01	272	0.8577981E 00
273	-0.3863424E 00	274	0.3168389E 01	275	0.3307714E 00	276	0.8285038E 00
277	0.9797426E 00	278	-0.2144802E 00	279	0.0	280	0.0
281	-0.7713985E 00	282	0.0	283	-0.5143262E 00	284	-0.1262039E 00
285	0.0	286	0.1057504E 01	287	0.6124240E 00	288	-0.1142810E 01
289	0.0	290	0.0	291	0.6648805E 00	292	0.0
293	0.0	294	0.1057504E 01	295	0.0	296	0.0
297	0.1109974E 01	298	0.9752331E 00	299	0.0	300	0.0
301	0.0	302	-0.5143262E 00	303	-0.1166491E 01	304	0.0
305	0.2370443E 00	306	0.0	307	0.0	308	0.0
309	0.0	310	0.0	311	0.1057504E 01	312	0.6906831E 00
313	-0.1201338E 01	314	0.5659661E 00	315	0.0	316	0.0
317	0.6159479E 00	318	0.2845502E 00	319	0.0	320	0.0
321	0.0	322	0.0	323	0.4649846E 00	324	0.0
325	0.2308410E 00	326	0.0	327	0.0	328	0.0
329	0.0	330	0.0	331	0.0	332	0.0
333	-0.1295054E 01	334	0.5659661E 00	335	0.0	336	0.0
337	0.6725259E 00	338	0.0	339	0.1085712E 00	340	0.2845502E 00
341	0.1426241E 01	342	0.0	343	0.0	344	0.0
345	0.0	346	0.0	347	0.0	348	0.0
349	0.0	350	0.0	351	-0.6692418E 00	352	0.0
353	-0.1295054E 01	354	0.2845502E 00	355	0.1063651E 01	356	0.0
357	0.0	358	0.0	359	0.0	360	0.0
361	0.0	362	0.0	363	0.0	364	0.0
365	0.1844683E 00	366	0.2093776E 01	367	-0.1349670E 01	368	-0.1172079E 01
369	0.1450625E 01	370	0.0	371	0.0	372	0.0
373	0.0	374	0.0	375	0.7574350E-01	376	0.2014798E 01
377	-0.1349670E 01	378	-0.6577538E 00	379	0.4699914E-01	380	0.0
381	0.0	382	0.0	383	0.0	384	0.0
385	0.8931599E 00						

Bootstrap Detection Algorithm for Incipient Failures

One problem which may occur in developing of the incipient failure detection algorithms presented in Figures 14 and 15 is that if a failure has occurred and has not been observed or has not been recorded in either a 3M or NOAP data bases, we would not have had it in the training data. Furthermore, the decision as to when an engine changes from good to bad prior to the occurrence of a failure is rather arbitrary even when we leave a reasonable gap between these two. This is clear from the fact that some engine failures were anticipated by as much as 160 engine hours while others only 20 hours in advance of the failure.

An approach to overcome these difficulties is to examine Figure 14 and use it to define the occurrence of the failures. That is, if Figure 14 shows that we have been able to anticipate a failure earlier than we had thought, this additional data should be put in the failure class of the training data and conversely if the failure could not be detected until much closer than we had anticipated more of these cases should be put in the good class. Furthermore, if there are indications of failures which we did not see, these should be left out of the algorithm development since the failure may have occurred and not been correctly reported. That is, the 3M data cannot be taken as 100% reliable! When this is accomplished, one expects to significantly reduce the probability of error associated with the new algorithm. We define this procedure as the bootstrap procedure.

This "bootstrapping" was performed on the present data set and the detection statistic calculated from the resulting algorithm is presented in Figure 17 and Table 5. Figure 17 and Table 5 have the same format as Figure 14 and Table 3. The net result of the bootstrap was to improve the probability of error from .14 to .033. Thus, the calls of failures are much stronger than they were in Figure 14, however, we have lost the ability to see some of the failures. Again, the detection statistics listed in table 5 are 10 less than those plotted in

FIGURE 17 DETECTION STATISTIC FOR
BOOTSTRAP DETECTION OF INCIPIENT ENGINE FAILURES

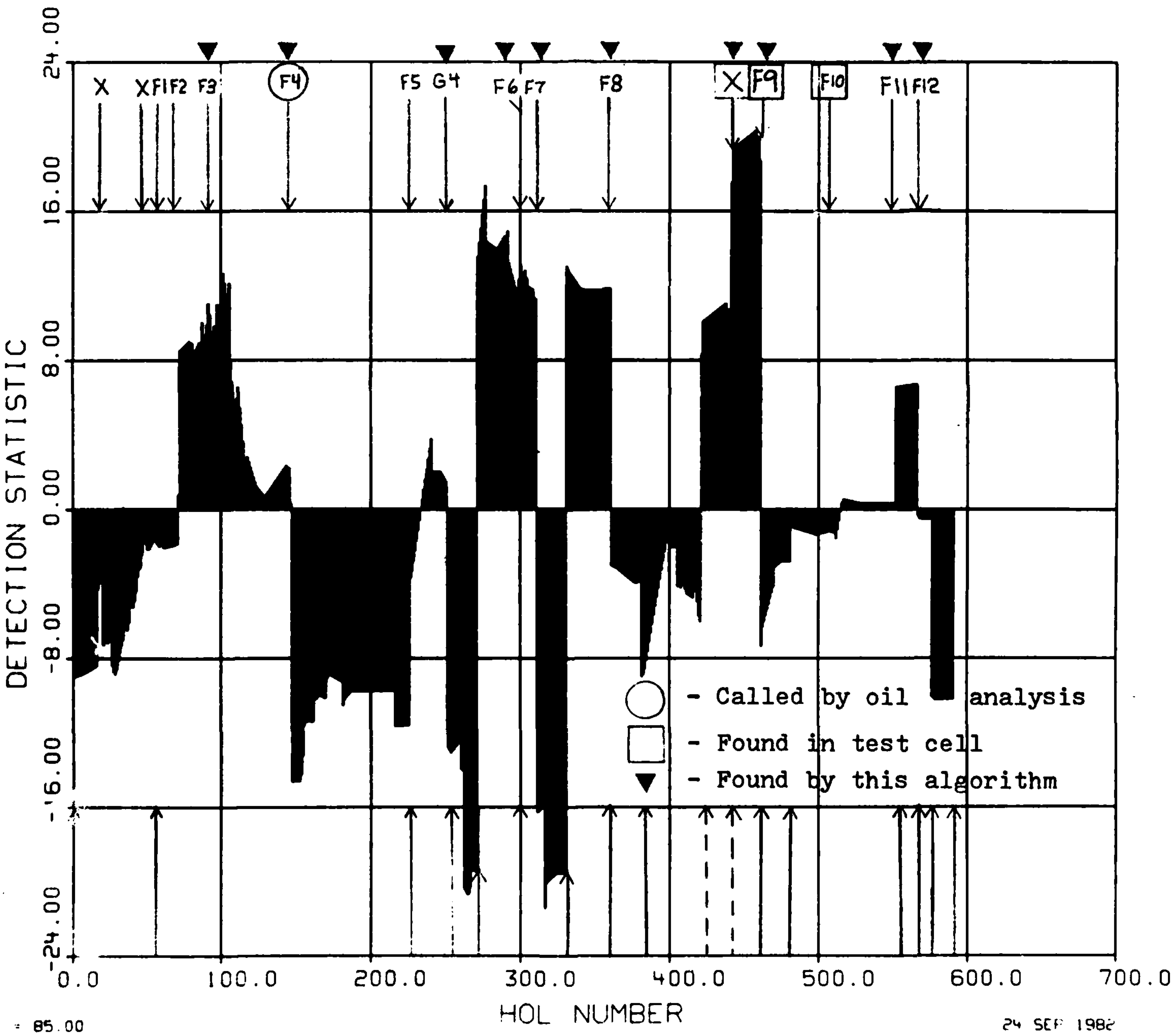


TABLE 5

DETECTION STATISTIC FOR BOOT STRAP INCIPIENT ENGINE FAILURE DETECTOR

HOL	DETECTION STAT	HOL	DETECTION STAT	HOL	DETECTION STAT	HOL	DETECTION STAT
1	-0.1962062E 02	2	-0.1959218E 02	3	-0.1956310E 02	4	-0.1952919E 02
5	-0.1949530E 02	6	-0.1946060E 02	7	-0.1942331E 02	8	-0.1938602E 02
9	-0.1934508E 02	10	-0.1929747E 02	11	-0.1924983E 02	12	-0.1920221E 02
13	-0.1915460E 02	14	-0.1910696E 02	15	-0.1905936E 02	16	-0.1490845E 02
17	-0.1459046E 02	18	-0.1409260E 02	19	-0.1436052E 02	20	-0.1791605E 02
21	-0.1717018E 02	22	-0.1657716E 02	23	-0.1778517E 02	24	-0.1717883E 02
25	-0.1647765E 02	26	-0.1901791E 02	27	-0.1935194E 02	28	-0.1948158E 02
29	-0.1918619E 02	30	-0.1873013E 02	31	-0.1830605E 02	32	-0.1792888E 02
33	-0.1763937E 02	34	-0.1678902E 02	35	-0.1694510E 02	36	-0.1711482E 02
37	-0.1669809E 02	38	-0.1554325E 02	39	-0.1576331E 02	40	-0.1588961E 02
41	-0.1554239E 02	42	-0.1502516E 02	43	-0.1421644E 02	44	-0.1385991E 02
45	-0.1373675E 02	46	-0.1302389E 02	47	-0.1225700E 02	48	-0.1213933E 02
49	-0.1244738E 02	50	-0.1275542E 02	51	-0.1275175E 02	52	-0.1258580E 02
53	-0.1241985E 02	54	-0.1225389E 02	55	-0.1223000E 02	56	-0.1237954E 02
57	-0.1249442E 02	58	-0.1260929E 02	59	-0.1252314E 02	60	-0.1246335E 02
61	-0.1267003E 02	62	-0.1265682E 02	63	-0.1264361E 02	64	-0.1262946E 02
65	-0.1261107E 02	66	-0.1259268E 02	67	-0.1257429E 02	68	-0.1254627E 02
69	-0.1251757E 02	70	-0.1248887E 02	71	-0.9840500E 01	72	-0.2103108E 01
73	-0.2023820E 01	74	-0.1944521E 01	75	-0.1865225E 01	76	-0.1785935E 01
77	-0.1706642E 01	78	-0.1627329E 01	79	-0.1677001E 01	80	-0.1726657E 01
81	-0.2149347E 01	82	-0.2146747E 01	83	-0.2034892E 01	84	-0.1876164E 01
85	-0.1683126E 01	86	-0.1732603E 01	87	-0.5975485E 00	88	-0.1309823E 01
89	-0.2444041E 01	90	-0.7339540E 00	91	0.4106972E 00	92	-0.1856200E 00
93	-0.1132482E 01	94	-0.1120761E 01	95	-0.7811863E 00	96	-0.1067675E 01
97	0.3622551E 00	98	-0.1080265E 00	99	0.3842993E 00	100	0.1414097E 01
101	0.2041356E 01	102	0.1507122E 01	103	0.6000788E 00	104	0.9097822E 00
105	0.1503195E 01	106	-0.2752731E 01	107	-0.3791129E 01	108	-0.4829443E 01
109	-0.5658771E 01	110	-0.4679473E 01	111	-0.4092389E 01	112	-0.5189363E 01
113	-0.6095848E 01	114	-0.7002342E 01	115	-0.7908897E 01	116	-0.8381500E 01
117	-0.7821368E 01	118	-0.8106318E 01	119	-0.8375325E 01	120	-0.8644333E 01
121	-0.8913341E 01	122	-0.9182364E 01	123	-0.9427608E 01	124	-0.9530196E 01
125	-0.9632792E 01	126	-0.9735392E 01	127	-0.9837989E 01	128	-0.9944366E 01
129	-0.9926025E 01	130	-0.9807775E 01	131	-0.9689524E 01	132	-0.9571272E 01
133	-0.9453003E 01	134	-0.9334761E 01	135	-0.9216508E 01	136	-0.9098241E 01
137	-0.8979988E 01	138	-0.8861744E 01	139	-0.8743486E 01	140	-0.8625222E 01
141	-0.8506972E 01	142	-0.8388722E 01	143	-0.8270462E 01	144	-0.8424775E 01
145	-0.8408436E 01	146	-0.1032615E 02	147	-0.2524408E 02	148	-0.2523788E 02
149	-0.2523170E 02	150	-0.2522549E 02	151	-0.2521861E 02	152	-0.2521143E 02
153	-0.2486789E 02	154	-0.2385139E 02	155	-0.2223325E 02	156	-0.2202670E 02
157	-0.2201480E 02	158	-0.2200291E 02	159	-0.2199867E 02	160	-0.2280970E 02
161	-0.2202075E 02	162	-0.2083493E 02	163	-0.2078619E 02	164	-0.2060432E 02
165	-0.2061734E 02	166	-0.2063036E 02	167	-0.2064336E 02	168	-0.2070280E 02
169	-0.2076224E 02	170	-0.1966783E 02	171	-0.1897385E 02	172	-0.1947600E 02
173	-0.1952287E 02	174	-0.1956975E 02	175	-0.1961662E 02	176	-0.1966348E 02
177	-0.1971036E 02	178	-0.1975725E 02	179	-0.1980411E 02	180	-0.1985098E 02
181	-0.2113077E 02	182	-0.2080798E 02	183	-0.2070581E 02	184	-0.2060365E 02
185	-0.2050146E 02	186	-0.2039926E 02	187	-0.2039804E 02	188	-0.2039682E 02
189	-0.2039561E 02	190	-0.2039439E 02	191	-0.2039317E 02	192	-0.2039195E 02
193	-0.2039073E 02	194	-0.2038951E 02	195	-0.2038829E 02	196	-0.2038708E 02
197	-0.2038586E 02	198	-0.2038463E 02	199	-0.2038342E 02	200	-0.2038219E 02

TABLE 5

DETECTION STATISTIC FOR BOOT STRAP INCIPIENT ENGINE FAILURE DETECTOR

CONTINUED

HOL	DETECTION STAT	HOL	DETECTION STAT	HOL	DETECTION STAT	HOL	DETECTION STAT
201	-0.2038100E 02	202	-0.2037976E 02	203	-0.2037854E 02	204	-0.2037733E 02
205	-0.2037611E 02	206	-0.2037488E 02	207	-0.2037367E 02	208	-0.2037245E 02
209	-0.2037123E 02	210	-0.2037001E 02	211	-0.2036880E 02	212	-0.2036755E 02
213	-0.2036635E 02	214	-0.2036511E 02	215	-0.2036391E 02	216	-0.2226527E 02
217	-0.2226163E 02	218	-0.2225798E 02	219	-0.2225432E 02	220	-0.2225067E 02
221	-0.2224698E 02	222	-0.2224333E 02	223	-0.2223967E 02	224	-0.2223601E 02
225	-0.2223236E 02	226	-0.1431299E 02	227	-0.1393000E 02	228	-0.1338360E 02
229	-0.1283721E 02	230	-0.1229082E 02	231	-0.1174444E 02	232	-0.1119805E 02
233	-0.1065165E 02	234	-0.1010525E 02	235	-0.9558861E 01	236	-0.9012458E 01
237	-0.8466069E 01	238	-0.7919685E 01	239	-0.7373298E 01	240	-0.6826912E 01
241	-0.8599792E 01	242	-0.8598331E 01	243	-0.8596866E 01	244	-0.8595394E 01
245	-0.8593920E 01	246	-0.8592455E 01	247	-0.8730735E 01	248	-0.8869055E 01
249	-0.9007354E 01	250	-0.9145660E 01	251	-0.2338123E 02	252	-0.2353548E 02
253	-0.2368979E 02	254	-0.2358624E 02	255	-0.2348260E 02	256	-0.2337906E 02
257	-0.2327542E 02	258	-0.2317183E 02	259	-0.2306827E 02	260	-0.2457755E 02
261	-0.2464409E 02	262	-0.3103990E 02	263	-0.3118915E 02	264	-0.3133838E 02
265	-0.3130577E 02	266	-0.3095833E 02	267	-0.3001106E 02	268	-0.3004057E 02
269	-0.3007007E 02	270	-0.3009959E 02	271	0.2914948E 01	272	0.3679317E 01
273	0.4443691E 01	274	0.5208057E 01	275	0.5972332E 01	276	0.6736633E 01
277	0.3718952E 01	278	0.3661224E 01	279	0.3603477E 01	280	0.3545755E 01
281	0.3488029E 01	282	0.3430308E 01	283	0.3372602E 01	284	0.3314880E 01
285	0.3454018E 01	286	0.3594831E 01	287	0.3735624E 01	288	0.3876434E 01
289	0.4017258E 01	290	0.3945745E 01	291	0.4288360E 01	292	0.2587406E 01
293	0.2260973E 01	294	0.1937800E 01	295	0.1614618E 01	296	0.1291432E 01
297	0.8799934E 00	298	0.8390166E 00	299	0.1712259E 01	300	0.2463924E 01
301	0.1469557E 01	302	0.2024706E 01	303	0.2182888E 01	304	0.1743152E 01
305	0.1303401E 01	306	0.1259049E 01	307	0.1214696E 01	308	0.1170332E 01
309	0.6901312E 00	310	0.6457253E 00	311	-0.2690131E 02	312	-0.2682573E 02
313	-0.2675012E 02	314	-0.2667451E 02	315	-0.2659894E 02	316	-0.3205127E 02
317	-0.3069557E 02	318	-0.3061824E 02	319	-0.3054265E 02	320	-0.3046701E 02
321	-0.3039143E 02	322	-0.3031581E 02	323	-0.3024020E 02	324	-0.3016463E 02
325	-0.3019638E 02	326	-0.3019342E 02	327	-0.3019044E 02	328	-0.3018748E 02
329	-0.3018452E 02	330	-0.3018153E 02	331	0.2401726E 01	332	0.2195199E 01
333	0.2015784E 01	334	0.1903860E 01	335	0.1791956E 01	336	0.1680039E 01
337	0.1568163E 01	338	0.1456232E 01	339	0.1344314E 01	340	0.1232411E 01
341	0.1198826E 01	342	0.1176446E 01	343	0.1154060E 01	344	0.1142900E 01
345	0.1142977E 01	346	0.1143036E 01	347	0.1143112E 01	348	0.1143172E 01
349	0.1143241E 01	350	0.1143316E 01	351	0.1143385E 01	352	0.1143455E 01
353	0.1143525E 01	354	0.1143597E 01	355	0.1176476E 01	356	0.1221868E 01
357	0.1226315E 01	358	0.1230757E 01	359	0.1235199E 01	360	0.1239654E 01
361	-0.1362100E 02	362	-0.1366862E 02	363	-0.1371619E 02	364	-0.1376377E 02
365	-0.1381141E 02	366	-0.1387751E 02	367	-0.1394363E 02	368	-0.1400972E 02
369	-0.1407580E 02	370	-0.1414192E 02	371	-0.1420803E 02	372	-0.1427411E 02
373	-0.1434023E 02	374	-0.1440637E 02	375	-0.1447251E 02	376	-0.1453877E 02
377	-0.1457657E 02	378	-0.1454457E 02	379	-0.1451252E 02	380	-0.1448045E 02
381	-0.1959760E 02	382	-0.1948567E 02	383	-0.1919011E 02	384	-0.1871608E 02
385	-0.1822960E 02	386	-0.1774310E 02	387	-0.1725661E 02	388	-0.1677010E 02
389	-0.1628362E 02	390	-0.1579714E 02	391	-0.1531064E 02	392	-0.1482414E 02
393	-0.1433764E 02	394	-0.1385114E 02	395	-0.1336464E 02	396	-0.1287815E 02
397	-0.1239165E 02	398	-0.1235971E 02	399	-0.1187321E 02	400	-0.1263375E 02

TABLE 5
DETECTION STATISTIC FOR BOOT STRAP INCIPIENT ENGINE FAILURE DETECTOR
CONTINUED

HOL	DETECTION STAT	HOL	DETECTION STAT	HOL	DETECTION STAT	HOL	DETECTION STAT
401	-0.1263817E 02	402	-0.1264258E 02	403	-0.1264700E 02	404	-0.1265143E 02
405	-0.1474804E 02	406	-0.1475246E 02	407	-0.1481272E 02	408	-0.1464708E 02
409	-0.1467718E 02	410	-0.1490915E 02	411	-0.1514112E 02	412	-0.1518504E 02
413	-0.1524905E 02	414	-0.1531308E 02	415	-0.1535404E 02	416	-0.1500125E 02
417	-0.1450413E 02	418	-0.1556096E 02	419	-0.1632675E 02	420	-0.1663373E 02
421	-0.2304174E 01	422	-0.5502502E 00	423	-0.4863093E 00	424	-0.4223724E 00
425	-0.3584309E 00	426	-0.2944952E 00	427	-0.2305545E 00	428	-0.1666139E 00
429	-0.1026778E 00	430	-0.3873801E-01	431	0.2520019E-01	432	0.8914042E-01
433	0.1530784E 00	434	0.2170172E 00	435	0.2809541E 00	436	0.3448936E 00
437	0.4088349E 00	438	0.1820523E-01	439	0.8214551E-01	440	-0.1232711E 01
441	0.6920906E 01	442	0.8752373E 01	443	0.8816313E 01	444	0.8880250E 01
445	0.8944189E 01	446	0.9008128E 01	447	0.9072067E 01	448	0.9136009E 01
449	0.9199945E 01	450	0.9263886E 01	451	0.9327823E 01	452	0.9391761E 01
453	0.9455697E 01	454	0.9519634E 01	455	0.9583572E 01	456	0.9647512E 01
457	0.9711452E 01	458	0.9320731E 01	459	0.9384558E 01	460	0.8069884E 01
461	-0.1796280E 02	462	-0.1690112E 02	463	-0.1659821E 02	464	-0.1629526E 02
465	-0.1599236E 02	466	-0.1568939E 02	467	-0.1538645E 02	468	-0.1508352E 02
469	-0.1478054E 02	470	-0.1371130E 02	471	-0.1364623E 02	472	-0.1358118E 02
473	-0.1351611E 02	474	-0.1345104E 02	475	-0.1342785E 02	476	-0.1342563E 02
477	-0.1342338E 02	478	-0.1342115E 02	479	-0.1341893E 02	480	-0.1341667E 02
481	-0.1155621E 02	482	-0.1158137E 02	483	-0.1160642E 02	484	-0.1163158E 02
485	-0.1165663E 02	486	-0.1168179E 02	487	-0.1170684E 02	488	-0.1173200E 02
489	-0.1175716E 02	490	-0.1178221E 02	491	-0.1180737E 02	492	-0.1183242E 02
493	-0.1185758E 02	494	-0.1188262E 02	495	-0.1190779E 02	496	-0.1193283E 02
497	-0.1195800E 02	498	-0.1198316E 02	499	-0.1196056E 02	500	-0.1193937E 02
501	-0.1191818E 02	502	-0.1189697E 02	503	-0.1187578E 02	504	-0.1185458E 02
505	-0.1183338E 02	506	-0.1178279E 02	507	-0.1180631E 02	508	-0.1182983E 02
509	-0.1185334E 02	510	-0.1187685E 02	511	-0.1216265E 02	512	-0.1168693E 02
513	-0.1121120E 02	514	-0.1073548E 02	515	-0.1025976E 02	516	-0.1007924E 02
517	-0.1009565E 02	518	-0.1011205E 02	519	-0.1012846E 02	520	-0.1014487E 02
521	-0.1016127E 02	522	-0.1017767E 02	523	-0.1019407E 02	524	-0.1021047E 02
525	-0.1022687E 02	526	-0.1024327E 02	527	-0.1025967E 02	528	-0.1027608E 02
529	-0.1027780E 02	530	-0.1027810E 02	531	-0.1027841E 02	532	-0.1027871E 02
533	-0.1027901E 02	534	-0.1027932E 02	535	-0.1027962E 02	536	-0.1027993E 02
537	-0.1028023E 02	538	-0.1028053E 02	539	-0.1028084E 02	540	-0.1028115E 02
541	-0.1028145E 02	542	-0.1028175E 02	543	-0.1028206E 02	544	-0.1028236E 02
545	-0.1028267E 02	546	-0.1028297E 02	547	-0.1028327E 02	548	-0.1028358E 02
549	-0.1028389E 02	550	-0.1028419E 02	551	-0.4043463E 01	552	-0.4031700E 01
553	-0.4019934E 01	554	-0.4008173E 01	555	-0.3996408E 01	556	-0.3984646E 01
557	-0.3972884E 01	558	-0.3961120E 01	559	-0.3954135E 01	560	-0.3948922E 01
561	-0.3943711E 01	562	-0.3938496E 01	563	-0.3933288E 01	564	-0.3928076E 01
565	-0.3922860E 01	566	-0.1096580E 02	567	-0.1111254E 02	568	-0.1112401E 02
569	-0.1113548E 02	570	-0.1114697E 02	571	-0.1115842E 02	572	-0.1115207E 02
573	-0.1114126E 02	574	-0.1113054E 02	575	-0.1111971E 02	576	-0.2069785E 02
577	-0.2077744E 02	578	-0.2085701E 02	579	-0.2086021E 02	580	-0.2085777E 02
581	-0.2085532E 02	582	-0.2085286E 02	583	-0.2085040E 02	584	-0.2084796E 02
585	-0.2084552E 02	586	-0.2084306E 02	587	-0.2084061E 02	588	-0.2083815E 02
589	-0.2083571E 02	590	-0.2083325E 02				

Figure 17. Notice, that G5 has fallen below the threshold but still has a similar shape but G4 is now detected. It also has negative slopes and represents measurements immediately after the test cell. Thus, the discussion of G5 is also applicable in this case. The reader is also encouraged to "play with" adjusting the threshold on Figures 14 and 17.

Figure 18 and Table 6 present the relative importance vectors corresponding to Figure 17. We see that in the bootstrap case, the NOAP data is still the most important data, however, the importance of the test cell relative to the NOAP data has increased.

ADAPT Scatter Plot As Health Diagnostic Tool

Figure 13 showed that the dominant groupings which occurred in the plot of the first two eigendirections were due to the variation from engine to engine. However, there is also considerable variation within a given engine when the data was obtained over relatively long time periods. The two engines for which this was true have each been enclosed in solid curves and identified on Figure 13. These two engines are Serial # 687021 and 687279. For these two engines, information is available both when the engine was operating satisfactorily and where an incipient failure was anticipated, we see that there is considerable variation especially in the second eigendirection. Thus, if one were to replot the data presented in Figure 13 for one of these engines on a scale appropriate to that engine by itself, one might expect that more information on the engine health would be revealed. Figure 19 is such a projection.

On Figure 19, the symbols indicate the time from overhaul. That is, Symbol 1 occurred immediately after the overhaul followed by Symbol 2, and so-on up through 9. After 9, the symbols begin with the letters thus the letter A occurs immediately after 9 and X occurs very near to the time when the engine re-enters the test cell for another overhaul. There are two of each of the symbols on this figure. Using these symbol identifications, we can trace the life of the engine on this figure. When an incipient failure is likely it tends to be located in the upper left hand portion of the figure and when the engine is healthy it tends to be in the lower right hand corner of the figure.

Figure 19 is a good illustration of the use of the scatter plot to identify incipient failures. This may be considered "learning without a teacher" because the general procedure

FIGURE - 18 RELATIVE IMPORTANCE VECTOR FOR BOOT STRAP INCIPIENT ENGINE FAILURE DETECTOR

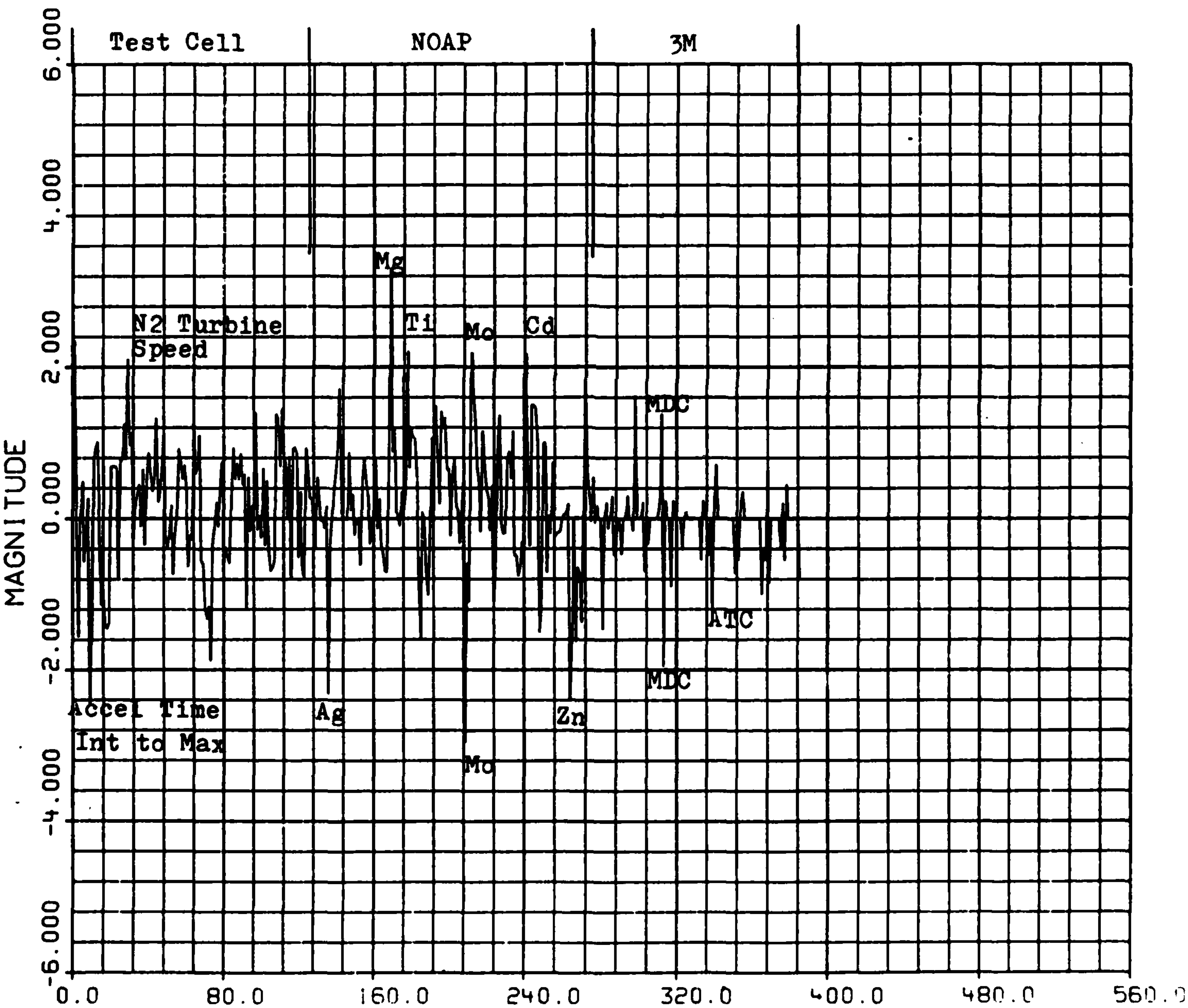


TABLE 6

RELATIVE IMPORTANCE OF EACH MEASUREMENT FOR DETECTING ENGINE FAILURES (REVISED)

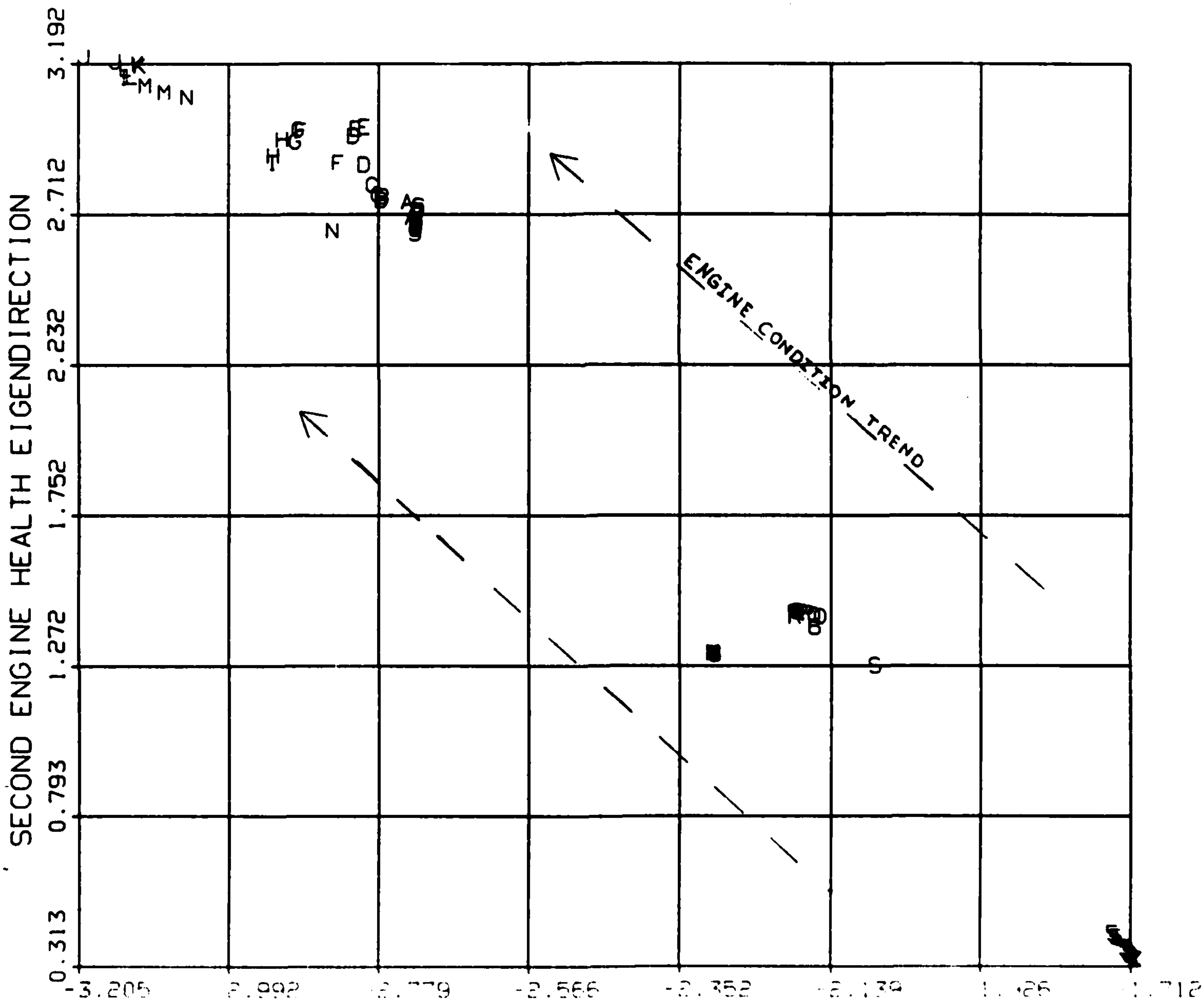
MEAS	REL IMPORTANCE	MEAS	REL IMPORTANCE	MEAS	REL IMPORTANCE	MEAS	REL IMPORTANCE
1	0.2350556E 01	2	0.0	3	-0.1560678E 01	4	0.0
5	0.4871071E 00	6	-0.5647349E 00	7	-0.2088890E 00	8	0.2664590E 00
9	-0.2460429E 01	10	-0.1619416E 01	11	0.7671485E 00	12	0.9370001E 00
13	0.1013504E 01	14	-0.1983878E 00	15	-0.1146592E 01	16	-0.1035009E 01
17	-0.1396945E 01	18	-0.1453564E 01	19	-0.1382540E 01	20	0.6871162E 00
21	0.6846229E 00	22	0.6926244E 00	23	0.6681978E 00	24	-0.7922701E 00
25	0.7944936E 00	26	0.7713941E 00	27	0.1249090E 01	28	0.7858145E 00
29	0.2102443E 01	30	0.9628623E 00	31	0.1133018E 01	32	-0.2584996E 00
33	0.1628425E 00	34	0.3493111E 00	35	0.4499439E 00	36	-0.1033568E 00
37	0.6477785E 00	38	-0.3474251E 00	39	0.5119747E 00	40	0.8668123E 00
41	0.5946092E 00	42	0.3572509E 00	43	0.5290288E 00	44	0.1320721E 01
45	0.2170734E 00	46	0.3523064E 00	47	0.7052336E 00	48	0.1105405E 01
49	-0.2142078E 00	50	-0.3944288E 00	51	-0.2376921E 00	52	0.1761693E 00
53	-0.7326026E 00	54	-0.2074368E 00	55	0.2413153E-01	56	0.9147494E 00
57	0.7607517E 00	58	0.5168691E 00	59	0.6996319E 00	60	0.3718787E 00
61	-0.6361935E 00	62	-0.2166954E 00	63	-0.2796462E 00	64	0.1318728E 01
65	0.5882291E 00	66	0.6768234E 00	67	0.1100093E 01	68	-0.5592723E 00
69	-0.5928327E 00	70	-0.1190993E 01	71	-0.1330667E 01	72	-0.1156214E 01
73	-0.1878652E 01	74	-0.3390880E 00	75	-0.1292088E 00	76	0.2168092E 00
77	-0.1075145E 00	78	0.4825306E 00	79	0.7514060E 00	80	-0.6071343E 00
81	-0.3769094E 00	82	-0.5122188E 00	83	-0.5859075E 00	84	0.2730539E 00
85	0.9315813E 00	86	0.5189868E 00	87	0.7318804E 00	88	0.5133194E 00
89	0.8559369E 00	90	0.4449897E 00	91	0.5902824E 00	92	-0.1172622E 01
93	0.5481842E 00	94	-0.1698582E 00	95	0.1805760E 00	96	-0.2119389E 00
97	0.1394511E 01	98	-0.1475707E 00	99	0.4145646E-01	100	-0.2522351E 00
101	0.6618216E 00	102	-0.3544710E 00	103	0.5059418E 00	104	-0.4377368E 00
105	-0.6946757E 00	106	-0.6488169E 00	107	-0.5612956E 00	108	0.1380219E 01
109	0.1323287E 01	110	0.6910790E 00	111	0.1445089E 01	112	0.7967729E 00
113	0.7436133E 00	114	0.1502782E-01	115	0.8124371E 00	116	-0.7881659E 00
117	0.9231129E 00	118	0.9381897E 00	119	0.8572121E 00	120	-0.5083837E 00
121	0.3536853E 00	122	-0.6891023E 00	123	-0.7853536E 00	124	0.9263687E 00
125	0.6506393E 00	126	0.2694795E 00	127	0.2612856E 00	128	0.3944593E-03
129	-0.3784605E 00	130	0.5405067E 00	131	0.2434466E 00	132	-0.3409026E-01
133	0.1797749E-01	134	-0.1274137E 00	135	0.1594490E 00	136	-0.2314404E 01
137	-0.3291377E 00	138	0.2308474E-01	139	0.3993391E 00	140	0.6236750E 00
141	0.9394475E 00	142	0.1713243E 01	143	0.9994709E-01	144	0.0
145	0.0	146	0.0	147	0.8714134E 00	148	0.1120678E 00
149	0.3172456E 00	150	-0.2164214E 00	151	-0.8112099E-02	152	0.0
153	-0.6129599E 00	154	0.5219650E 00	155	0.7904097E 00	156	0.4523060E 00
157	0.2880386E 00	158	-0.3327695E 00	159	-0.2579585E-01	160	-0.3736235E 00
161	0.7746894E 00	162	-0.1309187E 00	163	0.2591209E 00	164	-0.3315979E 00
165	-0.4580608E 00	166	-0.6993684E 00	167	-0.7054987E 00	168	0.7288411E 00
169	0.3305656E 01	170	0.8816296E 00	171	0.1200941E 01	172	0.9194040E-01
173	0.4641278E-01	174	-0.9997463E-01	175	0.3597123E 00	176	0.2273871E-02
177	0.3524963E 00	178	0.2203491E 01	179	0.6694518E 00	180	0.1188102E 01
181	0.1073471E 01	182	0.1049574E 01	183	0.5502053E 00	184	-0.8468496E 00
185	-0.1575537E 01	186	0.8066493E-01	187	-0.2028812E-01	188	-0.6890657E 00
189	-0.1014205E 01	190	-0.3542175E 00	191	0.1063432E 01	192	0.9015971E 00
193	0.1485291E 01	194	0.8338588E 00	195	0.1924150E 00	196	0.1408242E 01
197	0.1185418E 01	198	0.1327655E 01	199	0.6454791E 00	200	0.6506033E 00

TABLE 6
RELATIVE IMPORTANCE OF EACH MEASUREMENT FOR DETECTING ENGINE FAILURES (REVISED) CONTINUED

MEAS	REL IMPORTANCE	MEAS	REL IMPORTANCE	MEAS	REL IMPORTANCE	MEAS	REL IMPORTANCE
201	-0.2338961E 00	202	0.6099628E 00	203	0.7778049E 00	204	0.1470084E 00
205	0.9999675E-01	206	-0.3266416E 00	207	0.1801763E 00	208	0.5184118E 00
209	-0.2952331E 01	210	-0.5867363E 00	211	-0.1099499E 01	212	0.2189371E 01
213	0.1785126E 01	214	0.1397624E 01	215	0.6873295E 00	216	0.5181375E 00
217	-0.1722227E 00	218	0.1155660E 01	219	0.7371267E 00	220	0.3824214E 00
221	0.2834910E 00	222	-0.1596912E 00	223	0.4337877E 00	224	-0.1092763E 01
225	-0.7231663E 00	226	0.1078423E 01	227	0.1361989E 01	228	-0.6132606E-01
229	-0.2014700E 00	230	-0.1872661E 00	231	0.8066347E 00	232	0.8870583E 00
233	0.5299921E 00	234	0.1155257E 01	235	-0.4862702E 00	236	-0.4921619E 00
237	-0.7584127E 00	238	-0.6367360E 00	239	-0.3103380E 00	240	-0.3330597E 00
241	0.2167778E 01	242	0.4943612E 00	243	-0.3586167E 00	244	0.1499721E 01
245	0.1494547E 01	246	0.1459604E 01	247	0.1021918E 01	248	-0.1504533E 01
249	-0.1222542E 01	250	0.9934181E 00	251	0.1001630E 01	252	-0.7121636E 00
253	0.4694405E-01	254	-0.2005947E 00	255	0.7430838E 00	256	-0.2436665E 00
257	-0.2101782E 00	258	-0.1836745E 00	259	-0.1722492E 00	260	0.8233074E-02
261	0.5586087E-01	262	0.5564931E-01	263	0.1928283E 00	264	-0.2411417E 01
265	-0.1818116E 01	266	-0.3048605E-01	267	-0.1634645E 01	268	-0.6481668E 00
269	-0.7212032E 00	270	-0.1367660E 01	271	0.6987184E-01	272	0.1715071E 01
273	0.6328209E 00	274	0.2938306E 00	275	-0.3686108E-01	276	0.5419933E 00
277	-0.5450808E-01	278	0.1692515E 00	279	0.0	280	0.0
281	-0.1459476E 01	282	0.0	283	0.2111334E 00	284	-0.1316156E 00
285	0.0	286	0.2973636E 00	287	-0.4823576E 00	288	-0.4706759E 00
289	0.0	290	0.0	291	-0.4691060E 00	292	0.0
293	0.0	294	0.2973636E 00	295	0.0	296	0.0
297	-0.1629257E 00	298	0.1617276E 01	299	0.0	300	0.0
301	0.0	302	0.2111334E 00	303	-0.7007108E 00	304	0.0
305	-0.3324370E 00	306	0.0	307	0.0	308	0.0
309	0.0	310	0.0	311	0.2973636E 00	312	0.1381245E 01
313	-0.1947230E 01	314	0.2338753E 00	315	0.0	316	0.0
317	-0.8985617E 00	318	0.2360320E 00	319	0.0	320	0.0
321	0.0	322	0.0	323	-0.3865244E 00	324	0.0
325	0.8949584E-01	326	0.0	327	0.0	328	0.0
329	0.0	330	0.0	331	0.0	332	0.0
333	-0.5439314E 00	334	0.2338753E 00	335	0.0	336	0.0
337	-0.4926311E 00	338	0.0	339	-0.1386636E 01	340	0.2360320E 00
341	0.7106846E 00	342	0.0	343	0.0	344	0.0
345	0.0	346	0.0	347	0.0	348	0.0
349	0.0	350	0.0	351	-0.7234656E 00	352	0.0
353	-0.5439314E 00	354	0.2360320E 00	355	0.3574129E 00	356	0.0
357	0.0	358	0.0	359	0.0	360	0.0
361	0.0	362	0.0	363	0.0	364	0.0
365	-0.9999349E 00	366	-0.3870960E 00	367	-0.5509857E 00	368	0.6590769E 00
369	-0.8532407E 00	370	0.0	371	0.0	372	0.0
373	0.0	374	0.0	375	-0.3759096E 00	376	0.2006377E 00
377	-0.5509857E 00	378	0.4479434E 00	379	-0.1053595E-01	380	0.0
381	0.0	382	0.0	383	0.0	384	0.0
385	-0.7741758E 00	386	-0.1955916E 02	387	-0.2015359E 02	388	-0.2074805E 02
389	-0.2134247E 02	390	-0.2193690E 02	391	-0.2253134E 02	392	-0.2312576E 02
393	-0.2372021E 02	394	-0.2431465E 02	395	-0.2490906E 02	396	-0.2550349E 02
397	-0.2609792E 02	398	-0.3056189E 02	399	-0.3115636E 02	400	-0.3410484E 02

FIGURE - 19

PROJECTION ON FIRST AND SECOND ENGINE HEALTH EIGENDIRECTION (ENGINE 687279)



is to plot an engine on the scatter plot every time a new set of data is recorded. Under the assumption that when the engine leaves the overhaul facility, it is a healthy engine and aslong as its position on the scatter plot remains approximately the same, we assume it continues to be a healthy engine. When it begins to deviate significantly from the position, especially when this deviation is rapid, one should suspect that there is something unusual about the engine. If the deviation is also toward know failures, it is probably due to an impending failure. In these cases, extra effort should be made to diagnose this engine in the event that the automated classifiers have not already identified it. One action that could be taken if one were to use this technique and observe the engine deviating from its normal position would be to increase the frequency of oil samplings for that engine.

Clearly, the scatter plot is not a tool for the "sailor". It is laboratory tool which can be used by the more experienced laboratory technicians. It is not proposed a substitute for the automatic detection of incipient engine failures. The performances presented in this report do not include any enhancement which could be achieved by the use of the scatter plot approach. It is offered as an additional benefit which can be achieved if the ADAPT approach to deriving automated algorithms is incorporated and applied by qualified personnel. There is no additional cost for including this capability since the software is already required and the presentation of the information is merely the addition of a few printing instructions. Although the performances that are quoted in this report do not include any contribution that could be achieved by use of these scatter plots, examples such as those shown in Figure 19 suggests that a significant increase in performance is possible using these diagnostic aids. If effectively applied it is likely they could virtually eliminate any preflight and inflight engine aborts. It is recommended that this technique be investigated as part of the Phase II program and that its impact on both the cost of training, performing the analysis and the quality of the analysis be developed and reported as part of any follow on Phase II studies.

4.3 IDENTIFICATION OF FAILURES

In the preceding Section 4.2, we illustrated two algorithms for detecting unhealthy engines as well as an approach for using the ADAPT scatter plots for identifying unhealthy engines. In this section, we shall discuss two algorithms for determining the most likely cause of the incipient failure and which are suitable and proposed for implementation in the automated system. We shall also indicate an approach that may be used with the unique ADAPT analysis tools by experienced laboratory technicians or engine mechanics to assist in diagnoses of the engine's problems.

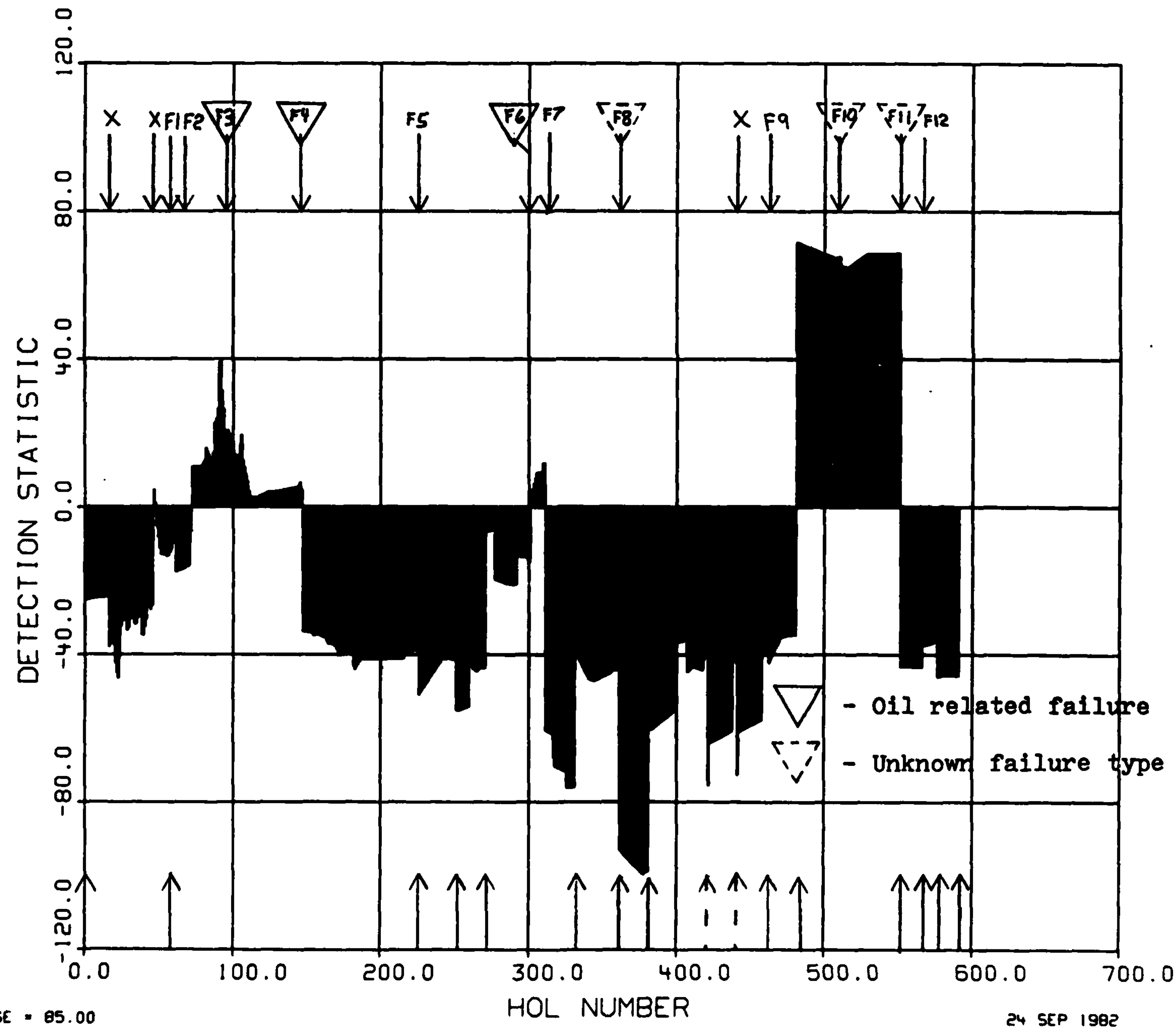
The two types of algorithms which have been developed to illustrate the diagnoses of an engine failure are the failure detection and the failure classification algorithms. These algorithms although conceptually very similar, often are quite different in both their physical basis for working and their performance. The failure detection algorithm is an algorithm which is developed by finding the best separation between a specific failure type and all other engines including both failed and unfailed engines. Thus, this algorithm both detects and identifies this type of failure. The alternative, the failure classification algorithm, is an algorithm which is derived to separate a specific type of failure from all other failures. It is derived using only histories for engines in which an incipient failure is expected. Although intuitively, one might expect this latter approach would provide somewhat better performance our experience has shown that this is not always the case and both types of algorithms should be investigated.

Oil Failure Detection Algorithm

To illustrate the failure detection algorithm, we have taken the same data that was used to derive the incipient failure detection algorithm and derived an algorithm for detecting engine oil problems. The results for this algorithm are presented in the same format as the previous algorithms presented in Figures 14 and 16. The corresponding figures for the oil failure detection algorithm are Figures 20 and 21. Tables 7 and 8, are an alternate presentation of the same information.

Figure 20 shows the detection statistic resulting from the application of the oil system failure detection algorithm to the entire 590 cases used in this study. The various failures are identified as before by the arrows along the top of the figure and the engine by the arrows along the bottom of the figure. Those failures which could be positively identified from either the 3M or NOAP data as oil system failures are included in solid facing triangles. They are failures F3, F4 and F6. The failure mode for the three failures included in dashed triangles could not be determined from the available 3M and NOAP data. For this reason, we must assume that they could be either oil system failures or non-oil system failures. The training was based on assuming that F3, F4 and F6 were oil system failures and omitting F8, F10 and F11 from the derivation of the algorithm.

FIGURE 20 DETECTION STATISTIC FOR DETECTION OF ENGINE OIL PROBLEMS



CASE = 85.00

24 SEP 1982

TABLE 7

DETECTION STATISTIC FOR DETECTION OF ENGINE OIL PROBLEMS (REVISED)

HOL	DETECTION STAT	HOL	DETECTION STAT	HOL	DETECTION STAT	HOL	DETECTION STAT
1	-0.4521710E 02	2	-0.4515012E 02	3	-0.4508139E 02	4	-0.4499973E 02
5	-0.4491808E 02	6	-0.4483876E 02	7	-0.4476709E 02	8	-0.4469542E 02
9	-0.4463609E 02	10	-0.4459941E 02	11	-0.4456265E 02	12	-0.4452599E 02
13	-0.4448924E 02	14	-0.4445259E 02	15	-0.4441589E 02	16	-0.5787340E 02
17	-0.5699388E 02	18	-0.5579056E 02	19	-0.5734668E 02	20	-0.6231561E 02
21	-0.6493423E 02	22	-0.6643373E 02	23	-0.6092596E 02	24	-0.5216843E 02
25	-0.4909785E 02	26	-0.5064685E 02	27	-0.5069073E 02	28	-0.5342087E 02
29	-0.5269263E 02	30	-0.5040923E 02	31	-0.4968080E 02	32	-0.5047729E 02
33	-0.5172043E 02	34	-0.5178052E 02	35	-0.5015779E 02	36	-0.4980490E 02
37	-0.4600749E 02	38	-0.5464908E 02	39	-0.5485431E 02	40	-0.5252792E 02
41	-0.5037225E 02	42	-0.4679459E 02	43	-0.4696693E 02	44	-0.4785336E 02
45	-0.4680455E 02	46	-0.1534827E 02	47	-0.1903943E 02	48	-0.2521664E 02
49	-0.2817331E 02	50	-0.3112984E 02	51	-0.3276688E 02	52	-0.3287547E 02
53	-0.3298410E 02	54	-0.3309274E 02	55	-0.3339110E 02	56	-0.3323145E 02
57	-0.3233580E 02	58	-0.3144016E 02	59	-0.2975473E 02	60	-0.2949234E 02
61	-0.3768967E 02	62	-0.3755495E 02	63	-0.3742020E 02	64	-0.3727917E 02
65	-0.3710939E 02	66	-0.3693959E 02	67	-0.3676982E 02	68	-0.3653310E 02
69	-0.3629161E 02	70	-0.3605009E 02	71	-0.2672935E 02	72	-0.9120211E 01
73	-0.9098031E 01	74	-0.9075890E 01	75	-0.9053735E 01	76	-0.9031554E 01
77	-0.9009360E 01	78	-0.8987170E 01	79	-0.8322865E 01	80	-0.7658648E 01
81	-0.4089635E 01	82	-0.5051376E 01	83	-0.5905597E 01	84	-0.6713437E 01
85	-0.7224070E 01	86	-0.5246345E 01	87	0.2870719E 01	88	0.3762153E 01
89	0.6551805E 01	90	0.1901726E 02	91	0.1999118E 02	92	0.1129259E 02
93	0.6469565E 01	94	0.6730375E 00	95	-0.3611567F 01	96	0.7018585E 00
97	-0.1989379E 00	98	-0.2900615E 01	99	-0.3043386E 01	100	-0.5733238E 01
101	-0.5919573E 01	102	-0.6044024E 01	103	-0.6148765E 01	104	-0.3331629E 01
105	-0.5997861E 00	106	-0.7429031E 01	107	-0.9258041E 01	108	-0.1108701E 02
109	-0.1309193E 02	110	-0.1578429E 02	111	-0.1716467E 02	112	-0.1744038E 02
113	-0.1741562E 02	114	-0.1739084E 02	115	-0.1736609E 02	116	-0.1745705E 02
117	-0.1704417E 02	118	-0.1692961E 02	119	-0.1672858E 02	120	-0.1652753E 02
121	-0.1632649E 02	122	-0.1612544E 02	123	-0.1595024E 02	124	-0.1592976E 02
125	-0.1590939E 02	126	-0.1588894E 02	127	-0.1586845E 02	128	-0.1579106E 02
129	-0.157[illegible]677E 02	130	-0.1565442E 02	131	-0.1557211E 02	132	-0.1548981E 02
133	-0.1540751E 02	134	-0.1532520E 02	135	-0.1524287E 02	136	-0.1516059E 02
137	-0.1507826E 02	138	-0.1499598E 02	139	-0.1491364E 02	140	-0.1483134E 02
141	-0.1474902E 02	142	-0.1466674E 02	143	-0.1458439E 02	144	-0.1431828E 02
145	-0.1342158E 02	146	-0.1540591E 02	147	-0.5378664E 02	148	-0.5384032E 02
149	-0.5389406E 02	150	-0.5394778E 02	151	-0.5395934E 02	152	-0.5394977E 02
153	-0.5413576E 02	154	-0.5471291E 02	155	-0.5482185E 02	156	-0.5446591E 02
157	-0.5459486E 02	158	-0.5472385E 02	159	-0.5487923E 02	160	-0.5508751E 02
161	-0.5529578E 02	162	-0.5518011E 02	163	-0.5620393E 02	164	-0.5695313E 02
165	-0.5702281E 02	166	-0.5709251E 02	167	-0.5716219E 02	168	-0.5744955E 02
169	-0.5773691E 02	170	-0.5854370E 02	171	-0.5941479E 02	172	-0.5913690E 02
173	-0.5918175E 02	174	-0.5922661E 02	175	-0.5927145E 02	176	-0.5931635E 02
177	-0.5936124E 02	178	-0.5940610E 02	179	-0.5945096E 02	180	-0.5949586E 02
181	-0.6307039E 02	182	-0.6393864E 02	183	-0.6328833E 02	184	-0.6263806E 02
185	-0.6198778E 02	186	-0.6133737E 02	187	-0.6132893E 02	188	-0.6132050E 02
189	-0.6131206E 02	190	-0.6130356E 02	191	-0.6129512E 02	192	-0.6128667E 02
193	-0.6127824E 02	194	-0.6126979E 02	195	-0.6126132E 02	196	-0.6125288E 02
197	-0.6124445E 02	198	-0.6123596E 02	199	-0.6122755E 02	200	-0.6121907E 02

TABLE 7

DETECTION STATISTIC FOR DETECTION OF ENGINE OIL PROBLEMS (REVISED)

CONTINUED

HOL	DETECTION STAT	HOL	DETECTION STAT	HOL	DETECTION STAT	HOL	DETECTION STAT
201	-0.6121062E 02	202	-0.6120216E 02	203	-0.6119374E 02	204	-0.6118527E 02
205	-0.6117685E 02	206	-0.6116840E 02	207	-0.6115993E 02	208	-0.6115150E 02
209	-0.6114307E 02	210	-0.6113461E 02	211	-0.6112614E 02	212	-0.6111769E 02
213	-0.6110925E 02	214	-0.6110080E 02	215	-0.6109236E 02	216	-0.5907713E 02
217	-0.5905182E 02	218	-0.5902646E 02	219	-0.5900113E 02	220	-0.5897577E 02
221	-0.5895042E 02	222	-0.5892508E 02	223	-0.5889972E 02	224	-0.5887436E 02
225	-0.5884900E 02	226	-0.7078619E 02	227	-0.7012132E 02	228	-0.6949969E 02
229	-0.6887796E 02	230	-0.6825630E 02	231	-0.6763464E 02	232	-0.6701297E 02
233	-0.6639133E 02	234	-0.6576970E 02	235	-0.6514806E 02	236	-0.6452641E 02
237	-0.6390472E 02	238	-0.6328311E 02	239	-0.6266139E 02	240	-0.6203973E 02
241	-0.6124368E 02	242	-0.6121765E 02	243	-0.6119159E 02	244	-0.6116551E 02
245	-0.6113943E 02	246	-0.6111336E 02	247	-0.6120908E 02	248	-0.6130479E 02
249	-0.6140051E 02	250	-0.6149620E 02	251	-0.7502585E 02	252	-0.7507082E 02
253	-0.7511588E 02	254	-0.7494720E 02	255	-0.7477852E 02	256	-0.7460983E 02
257	-0.7444112E 02	258	-0.7427237E 02	259	-0.7410371E 02	260	-0.6051379E 02
261	-0.6068962E 02	262	-0.6374948E 02	263	-0.6409325E 02	264	-0.6443701E 02
265	-0.6456508E 02	266	-0.6400262E 02	267	-0.6366547E 02	268	-0.6366292E 02
269	-0.6366039E 02	270	-0.6365785E 02	271	-0.2666772E 02	272	-0.2656647E 02
273	-0.2646526E 02	274	-0.2636403E 02	275	-0.2626303E 02	276	-0.2616193E 02
277	-0.3961717E 02	278	-0.3977402E 02	279	-0.3993089E 02	280	-0.4008772E 02
281	-0.4024454E 02	282	-0.4040135E 02	283	-0.4055818E 02	284	-0.4071497E 02
285	-0.4078430E 02	286	-0.4085068E 02	287	-0.4091702E 02	288	-0.4098343E 02
289	-0.4104976E 02	290	-0.4111140E 02	291	-0.4098241E 02	292	-0.3334883E 02
293	-0.3340411E 02	294	-0.3345348E 02	295	-0.3350285E 02	296	-0.3355225E 02
297	-0.3357726E 02	298	-0.3346989E 02	299	-0.3422375E 02	300	-0.3498473E 02
301	-0.1628125E 02	302	-0.1510483E 02	303	-0.1379288E 02	304	-0.1228214E 02
305	-0.1077140E 02	306	-0.1066873E 02	307	-0.1056603E 02	308	-0.1046339E 02
309	-0.8215460E 01	310	-0.8112670E 01	311	-0.8052750E 02	312	-0.8074570E 02
313	-0.8096388E 02	314	-0.8118204E 02	315	-0.8140021E 02	316	-0.8776804E 02
317	-0.9023306E 02	318	-0.9043175E 02	319	-0.9064984E 02	320	-0.9086807E 02
321	-0.9108620E 02	322	-0.9130432E 02	323	-0.9152251E 02	324	-0.9174069E 02
325	-0.9620345E 02	326	-0.9617155E 02	327	-0.9613971E 02	328	-0.9610789E 02
329	-0.9607605E 02	330	-0.9604425E 02	331	-0.5911107E 02	332	-0.6012444E 02
333	-0.6106972E 02	334	-0.6184552E 02	335	-0.6262129E 02	336	-0.6339709E 02
337	-0.6417284E 02	338	-0.6494861E 02	339	-0.6572441E 02	340	-0.6650018E 02
341	-0.6673294E 02	342	-0.6688811E 02	343	-0.6704326E 02	344	-0.6702736E 02
345	-0.6684039E 02	346	-0.6665344E 02	347	-0.6646645E 02	348	-0.6627951E 02
349	-0.6609254E 02	350	-0.6590559E 02	351	-0.6571860E 02	352	-0.6553166E 02
353	-0.6534470E 02	354	-0.6515771E 02	355	-0.6475597E 02	356	-0.6427237E 02
357	-0.6423618E 02	358	-0.6419998E 02	359	-0.6416380E 02	360	-0.6412762E 02
361	-0.1130978E 03	362	-0.1135536E 03	363	-0.1140094E 03	364	-0.1144651E 03
365	-0.1149213E 03	366	-0.1153318E 03	367	-0.1157425E 03	368	-0.1161532E 03
369	-0.1165636E 03	370	-0.1169743E 03	371	-0.1173849E 03	372	-0.1177955E 03
373	-0.1182061E 03	374	-0.1186168E 03	375	-0.1190273E 03	376	-0.1194380E 03
377	-0.1196360E 03	378	-0.1193759E 03	379	-0.1191159E 03	380	-0.1188558E 03
381	-0.8049367E 02	382	-0.8033293E 02	383	-0.8013596E 02	384	-0.7981914E 02
385	-0.7950040E 02	386	-0.7918178E 02	387	-0.7886307E 02	388	-0.7854453E 02
389	-0.7822578E 02	390	-0.7790710E 02	391	-0.7758838E 02	392	-0.7726978E 02
393	-0.7695107E 02	394	-0.7663243E 02	395	-0.7631372E 02	396	-0.7599506E 02
397	-0.7567638E 02	398	-0.5453011E 02	399	-0.5421155E 02	400	-0.5661084E 02

TABLE 7
DETECTION STATISTIC FOR DETECTION OF ENGINE OIL PROBLEMS (REVISED)
CONTINUED

HOL	DETECTION STAT	HOL	DETECTION STAT	HOL	DETECTION STAT	HOL	DETECTION STAT
401	-0.5652078E 02	402	-0.5643063E 02	403	-0.5634045E 02	404	-0.5625027E 02
405	-0.5425011E 02	406	-0.5415996E 02	407	-0.6470805E 02	408	-0.6429916E 02
409	-0.6370998E 02	410	-0.6354872E 02	411	-0.6338760E 02	412	-0.6348744E 02
413	-0.6363123E 02	414	-0.6377501E 02	415	-0.6395575E 02	416	-0.6410516E 02
417	-0.6411783E 02	418	-0.6131137E 02	419	-0.5974738E 02	420	-0.6052890E 02
421	-0.9544771E 02	422	-0.8405328E 02	423	-0.8383977E 02	424	-0.8362627E 02
425	-0.8341273E 02	426	-0.8319928E 02	427	-0.8298572E 02	428	-0.8277225E 02
429	-0.8255873E 02	430	-0.8234523E 02	431	-0.8213170E 02	432	-0.8191821E 02
433	-0.8170465E 02	434	-0.8149120E 02	435	-0.8127766E 02	436	-0.8106415E 02
437	-0.8085063E 02	438	-0.5980956E 02	439	-0.5959605E 02	440	-0.6227103E 02
441	-0.9262015E 02	442	-0.8097754E 02	443	-0.8076402E 02	444	-0.8055052E 02
445	-0.8033699E 02	446	-0.8012355E 02	447	-0.7990997E 02	448	-0.7969655E 02
449	-0.7948302E 02	450	-0.7926953E 02	451	-0.7905597E 02	452	-0.7884251E 02
453	-0.7862895E 02	454	-0.7841550E 02	455	-0.7820195E 02	456	-0.7798845E 02
457	-0.7777489E 02	458	-0.5673381E 02	459	-0.5652034E 02	460	-0.5919531E 02
461	-0.4958972E 02	462	-0.6216179E 02	463	-0.6137035E 02	464	-0.6057886E 02
465	-0.5978737E 02	466	-0.5899585E 02	467	-0.5820430E 02	468	-0.5741281E 02
469	-0.5662128E 02	470	-0.5550555E 02	471	-0.5536963E 02	472	-0.5523369E 02
473	-0.5509776E 02	474	-0.5496184E 02	475	-0.5489548E 02	476	-0.5486389E 02
477	-0.5483234E 02	478	-0.5480078E 02	479	-0.5476923E 02	480	-0.5473767E 02
481	0.5168835E 02	482	0.5151392E 02	483	0.5134027E 02	484	0.5116588E 02
485	0.5099222E 02	486	0.5081784E 02	487	0.5064418E 02	488	0.5046974E 02
489	0.5029535E 02	490	0.5012173E 02	491	0.4994731E 02	492	0.4977365E 02
493	0.4959927E 02	494	0.4942561E 02	495	0.4925117E 02	496	0.4907758E 02
497	0.4890315E 02	498	0.4872873E 02	499	0.4859407E 02	500	0.4845724E 02
501	0.4832040E 02	502	0.4818338E 02	503	0.4804654E 02	504	0.4790970E 02
505	0.4777274E 02	506	0.4727013E 02	507	0.4738904E 02	508	0.4750797E 02
509	0.4762689E 02	510	0.4774586E 02	511	0.4527795E 02	512	0.4517535E 02
513	0.4507271E 02	514	0.4497012E 02	515	0.4486754E 02	516	0.4500160E 02
517	0.4529344E 02	518	0.4558540E 02	519	0.4587735E 02	520	0.4616927E 02
521	0.4646117E 02	522	0.4675307E 02	523	0.4704500E 02	524	0.4733691E 02
525	0.4762880E 02	526	0.4792072E 02	527	0.4821252E 02	528	0.4850458E 02
529	0.4850961E 02	530	0.4851689E 02	531	0.4852406E 02	532	0.4853136E 02
533	0.4853857E 02	534	0.4854587E 02	535	0.4855307E 02	536	0.4856033E 02
537	0.4856755E 02	538	0.4857483E 02	539	0.4858209E 02	540	0.4858932E 02
541	0.4859656E 02	542	0.4860381E 02	543	0.4861104E 02	544	0.4861826E 02
545	0.4862553E 02	546	0.4863277E 02	547	0.4864001E 02	548	0.4864725E 02
549	0.4865451E 02	550	0.4866176E 02	551	-0.6340410E 02	552	-0.6340147E 02
553	-0.6339880E 02	554	-0.6339613E 02	555	-0.6339352E 02	556	-0.6339087E 02
557	-0.6338826E 02	558	-0.6338562E 02	559	-0.6338643E 02	560	-0.6338860E 02
561	-0.6339072E 02	562	-0.6339290E 02	563	-0.6339508E 02	564	-0.6339720E 02
565	-0.6339938E 02	566	-0.5275635E 02	567	-0.5752370E 02	568	-0.5741928E 02
569	-0.5731487E 02	570	-0.5721040E 02	571	-0.5710603E 02	572	-0.5691624E 02
573	-0.5670541E 02	574	-0.5649437E 02	575	-0.5628348E 02	576	-0.6596666E 02
577	-0.6591249E 02	578	-0.6585834E 02	579	-0.6586031E 02	580	-0.6585347E 02
581	-0.6584662E 02	582	-0.6583974E 02	583	-0.6583287E 02	584	-0.6582602E 02
585	-0.6581918E 02	586	-0.6581230E 02	587	-0.6580545E 02	588	-0.6579858E 02
589	-0.6579175E 02	590	-0.6578488E 02				

FIGURE - 21

LATIVE IMPORTANCE VECTOR FOR DETECTION OF
; WITH OIL PROBLEMS (590 CASE STUDY)

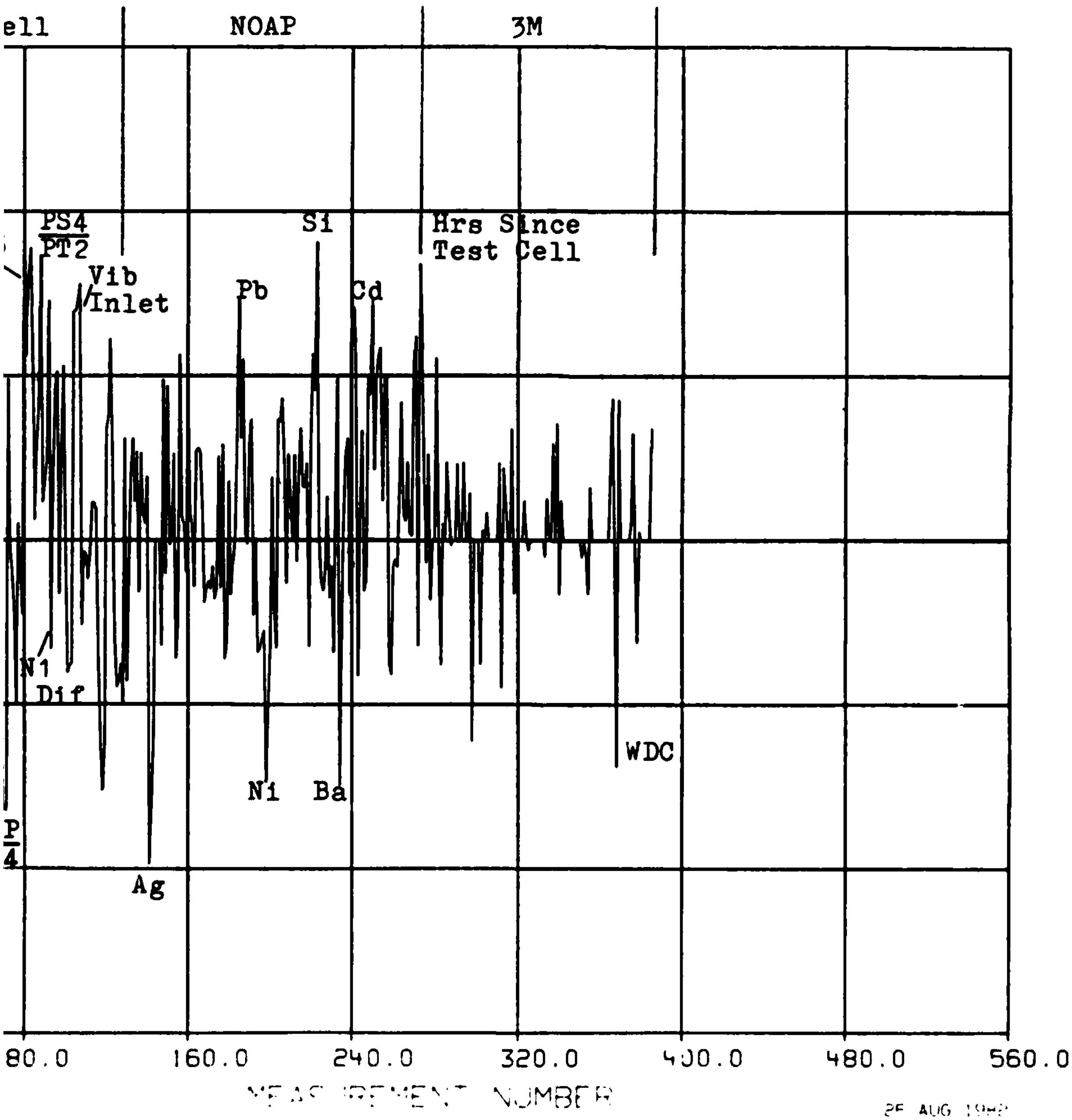


TABLE 8

RELATIVE IMPORTANCE OF EACH MEASUREMENT FOR DETECTING ENGINE OIL PROBLEMS

MEAS	REL IMPORTANCE	MEAS	REL IMPORTANCE	MEAS	REL IMPORTANCE	MEAS	REL IMPORTANCE
1	-0.2418262E 01	2	0.0	3	0.5676516E 00	4	0.0
5	0.1152585E 01	6	0.1494766E 01	7	0.1967426E 01	8	0.2168757E 01
9	0.1061979E 01	10	0.2054288E 01	11	-0.8719712E 00	12	0.5569094E 00
13	0.1546446E 01	14	-0.2867834E 00	15	0.2245564E 01	16	0.7586808E 00
17	0.3496408E 00	18	0.3831500E 00	19	0.5049412E 00	20	0.9669352E-01
21	0.1046626E 00	22	0.1335686E 00	23	0.6233966E-01	24	0.1948372E 01
25	-0.1041899E 01	26	0.3125426E 00	27	0.4953836E 00	28	0.1838050E 00
29	-0.5651498E 00	30	0.6110582E 00	31	0.1101623E 01	32	0.1653830E 01
33	0.1836454E 01	34	0.2148971E 01	35	0.2078351E 01	36	-0.1436592E 01
37	-0.1590499E 01	38	-0.1521893E 01	39	-0.1504582E 01	40	0.1927982E 01
41	0.4708685E 00	42	0.6391141E 00	43	0.7228303E 00	44	0.1257440E 01
45	0.3068637E 00	46	0.7748957E 00	47	0.8606864E 00	48	0.1079775E 01
49	-0.1364297E 01	50	-0.1023293E 01	51	-0.1051724E 01	52	-0.1988233E 01
53	0.3002660E 00	54	-0.1193917E 00	55	-0.4753585E 00	56	0.1908622E 01
57	0.4494479E 00	58	0.6053892E 00	59	0.6944556E 00	60	-0.8658311E 00
61	-0.3290282E 00	62	-0.1240253E 00	63	-0.2857785E 00	64	0.1185332E 01
65	0.2565850E 00	66	0.7570037E 00	67	0.8313430E 00	68	-0.7178714E 00
69	-0.3304303E 01	70	-0.3228662E 01	71	-0.3294879E 01	72	0.1963019E 01
73	-0.7646990E-01	74	-0.3750800E 00	75	-0.8267609E 00	76	-0.1985610E 01
77	0.2076616E 00	78	-0.3399788E 00	79	-0.8940097E 00	80	0.3412766E 01
81	0.2242834E 01	82	0.3240952E 01	83	0.3557802E 01	84	0.2459702E 01
85	0.2486113E 00	86	0.1203165E 01	87	0.1627942E 01	88	0.3469435E 01
89	0.4651977E 00	90	0.7367929E 00	91	0.9844245E 00	92	0.2917284E 01
93	-0.1321595E 01	94	0.7721908E 00	95	0.1880759E 01	96	0.2053205E 01
97	-0.6526671E 00	98	0.1125332E 01	99	0.2120112E 01	100	0.5519652E-01
101	-0.1611339E 01	102	-0.1522412E 01	103	-0.1499668E 01	104	0.2793410E 01
105	0.2787960E 01	106	0.2952950E 01	107	0.3117435E 01	108	-0.1029709E 01
109	-0.1426993E 00	110	-0.1633013E 00	111	-0.4696226E 00	112	-0.1589963E 00
113	0.4626241E 00	114	0.4560741E 00	115	0.3737598E 00	116	-0.1537663E 01
117	-0.2491955E 01	118	-0.3048921E 01	119	-0.2495313E 01	120	0.1357293E 01
121	0.1495761E 01	122	0.2448285E 01	123	0.1026726E 01	124	-0.1176741E 01
125	-0.1791548E 01	126	-0.1725914E 01	127	-0.1504606E 01	128	-0.1997179E 01
129	0.1236440E 01	130	-0.1714969E 01	131	-0.4730763E 00	132	0.8399087E 00
133	0.1235723E 01	134	0.4707155E 00	135	0.1075853E 01	136	-0.6280516E 00
137	0.1058532E 01	138	0.3135059E 00	139	0.2063149E 00	140	0.7723188E 00
141	-0.3936158E 01	142	-0.3277627E 01	143	-0.2425024E 01	144	0.0
145	0.0	146	0.0	147	-0.1280666E 01	148	0.1953464E 01
149	-0.4048893E 00	150	0.1874103E 01	151	-0.5638259E-01	152	0.0
153	0.1049383E 01	154	-0.1437867E 01	155	-0.1038083E 01	156	0.2257685E 01
157	0.2797036E 00	158	0.2012789E 00	159	-0.3837482E 00	160	0.1694963E 01
161	0.3481109E 00	162	0.1847674E 00	163	-0.5637074E 00	164	0.1080861E 01
165	0.1122557E 01	166	0.1078758E 01	167	0.4385017E 00	168	-0.7557914E 00
169	-0.5922006E 00	170	-0.5007264E 00	171	-0.5948474E 00	172	-0.3194240E 00
173	-0.7142216E 00	174	-0.5872569E 00	175	0.1015643E 01	176	-0.5817264E 00
177	0.1163823E 01	178	-0.1444377E 01	179	-0.1209264E 01	180	0.7144068E 00
181	-0.6645733E 00	182	-0.2787871E 00	183	0.5773872E-02	184	0.1205029E 01
185	0.2930667E 01	186	0.1242593E 01	187	0.2199418E 01	188	0.7488668E-01
189	-0.4613215E-01	190	0.1189469E 01	191	0.1467019E 01	192	-0.9153533E 00
193	0.1414517E-01	194	-0.1366282E 01	195	-0.1324845E 01	196	-0.1195214E 01
197	-0.1106676E 01	198	-0.2942664E 01	199	-0.1997234E 01	200	-0.1302794E 01

TABLE 8

RELATIVE IMPORTANCE OF EACH MEASUREMENT FOR DETECTING ENGINE OIL PROBLEMS

CONTINUED

MEAS	REL IMPORTANCE	MEAS	REL IMPORTANCE	MEAS	REL IMPORTANCE	MEAS	REL IMPORTANCE
201	0.7639055E 00	202	-0.8637064E 00	203	-0.1310699E 01	204	0.1468690E 01
205	0.1436934E 01	206	0.1724365E 01	207	0.9585184E 00	208	-0.5242338E 00
209	0.1042381E 01	210	0.4842970E 00	211	0.1197526E-01	212	0.1033923E 01
213	-0.2565488E 00	214	0.7282838E 00	215	0.1359038E 01	216	0.6527746E 00
217	0.6488618E 00	218	0.9293575E 00	219	-0.1290252E 01	220	0.1205351E 01
221	0.2263661E 01	222	0.1817854E 01	223	0.3627417E 01	224	0.1205307E-01
225	-0.5138509E 00	226	-0.6136214E 00	227	-0.3611482E 00	228	0.5268096E 00
229	-0.7020718E 00	230	-0.3217722E 00	231	-0.1359700E 01	232	0.4563986E 00
233	0.2001228E 01	234	-0.2982675E 01	235	-0.1036433E 01	236	0.3015338E 00
237	0.1058215E 01	238	0.1238249E 01	239	-0.6567301E 00	240	0.2789864E 01
241	0.2830204E 01	242	0.2231831E 01	243	-0.1644681E 01	244	0.2688462E 00
245	0.1327611E 01	246	-0.6104104E 00	247	-0.4805729E 00	248	0.1996140E 01
249	0.1766859E 01	250	0.2928832E 01	251	0.8568906E 00	252	0.1946238E 01
253	0.2243645E 01	254	0.2342038E 01	255	0.4851047E 00	256	0.2012338E 01
257	0.1988021E 01	258	-0.1488644E 01	259	-0.1629630E 01	260	-0.3152606E 00
261	-0.2323731E 00	262	-0.3220528E 00	263	0.5766020E 00	264	0.1674983E 01
265	0.3016576E 00	266	0.2328829E 00	267	0.9478950E 00	268	0.9643197E-01
269	0.5448101E-01	270	0.2073290E 01	271	0.2478647E 01	272	-0.1280073E 01
273	0.3359064E 01	274	0.2566501E 01	275	0.6808726E 00	276	-0.2703207E 00
277	0.1041262E 01	278	-0.7185768E 00	279	0.0	280	0.0
281	0.2211528E 01	282	0.0	283	-0.1512367E 01	284	0.2054158E 00
285	0.0	286	0.9446915E 00	287	0.3325064E 00	288	-0.5654065E-01
289	0.0	290	0.0	291	0.9261019E 00	292	0.0
293	0.0	294	0.9446915E 00	295	0.0	296	0.0
297	0.5774553E 00	298	-0.2445706E 01	299	0.0	300	0.0
301	0.0	302	-0.1512367E 01	303	0.1236845E 00	304	0.0
305	0.3395264E 00	306	0.0	307	0.0	308	0.0
309	0.0	310	0.0	311	0.9446915E 00	312	-0.1796387E 01
313	0.8811456E 00	314	0.5034212E 00	315	0.0	316	0.0
317	0.1355762E 01	318	-0.6493214E 00	319	0.0	320	0.0
321	0.0	322	0.0	323	0.4760497E 00	324	0.0
325	-0.1226207E 00	326	0.0	327	0.0	328	0.0
329	0.0	330	0.0	331	0.0	332	0.0
333	-0.1916602E 00	334	0.5034212E 00	335	0.0	336	0.0
337	0.1173024E 01	338	0.0	339	0.1415004E 01	340	-0.6493214E 00
341	0.4879941E 00	342	0.0	343	0.0	344	0.0
345	0.0	346	0.0	347	0.0	348	0.0
349	0.0	350	0.0	351	-0.2001366E 00	352	0.0
353	-0.1916602E 00	354	-0.6493214E 00	355	0.6477649E 00	356	0.0
357	0.0	358	0.0	359	0.0	360	0.0
361	0.0	362	0.0	363	0.0	364	0.0
365	0.9695607E 00	366	0.1723870E 01	367	-0.2406908E 00	368	-0.2756746E 01
369	0.1710374E 01	370	0.0	371	0.0	372	0.0
373	0.0	374	0.0	375	0.1980422E 00	376	0.1302674E 01
377	-0.2406908E 00	378	-0.1244377E 01	379	0.1037098E 00	380	0.0
381	0.0	382	0.0	383	0.0	384	0.0
385	0.1363225E 01						

However, Figure 20 shows the results of applying the algorithm to these three failure types. The algorithm would indicate that failure F8 was not a failure in the oil system whereas failures 10 and 11 were failures of the oil system. Once again for a detail description of what each of these failures are the reader is referred to Table 2. Tables 7 and 8 present the same information as Figures 20 and 21 in more detail so that a more careful analysis is possible by inspecting the figure.

Figure 21 shows the relative importance vector for the detection of engines with oil problems. The general shape of this curve is very similar to the incipient failure detection algorithm (Figure 16) except that the test cell measurements have become relatively more important then they were for the detection of incipient failures. This is primarily because the comparison between the reference test cell performance and the observed test cell values have become very significant. Although there are many wear metals which are important to both algorithms, there are elements which are important and differ between the two algorithms. It is interesting to note that 4 of the 5 most important wear metals for this algorithm (Na, Cd, Mn, V and Mg) are not used in the present NOAP program. The details of this relative importance vector are also presented in Table 8 so that the reader may perform his own analysis.

Oil Failure Classification Algorithm

As previously discussed, the classification algorithms are developed using only the failure cases. Figure 22 and Table 9 present the detection statistic for separating those failures which were engine oil failures from all of the other failures. Once again, the location of the engine oil failure is indicated by the downward facing triangle, the solid triangle, for those which were known from the truth data and the dashed triangles indicating those for which the truth data did not define whether the failure was in the oil system or not. The engine has also been identified on Figure 22. The only observations incorrectly identified by this algorithm are the last eight observations of failure F6. However, these are from the same engine as F7 and represent an example of the interpolation problem discussed in Section 3.5. Figure 23 and Table 10 present the corresponding relative importance vector for separating engine oil failures. It differs from the relative importance vector for detecting engine oil failures both in the detailed narrow band structure and in that the oil measurements are more important relative to the test cell measurements then they were for the oil failure detection algorithm. However, it is very similar to the relative importance vector for detecting incipient engine failures.

FIGURE 22 DETECTION STATISTIC FOR CLASSIFICATION OF ENGINE OIL PROBLEM

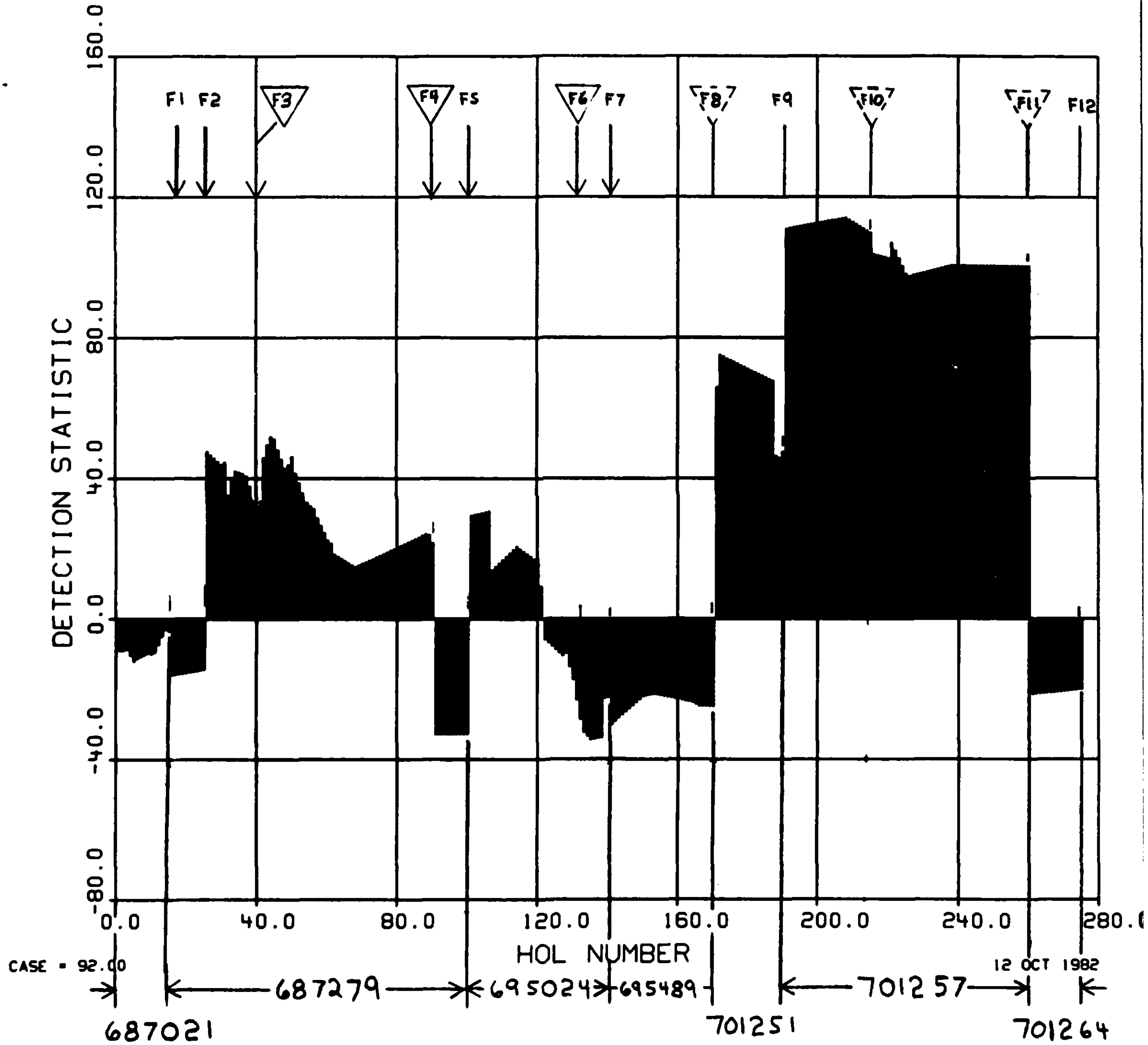


TABLE - 9

DETECTION STATISTIC FOR CLASSIFICATION OF ENGINE OIL PROBLEM

HOL	DETECTION STAT	HOL	DETECTION STAT	HOL	DETECTION STAT	HOL	DETECTION STAT
1	-0.4415204E 02	2	-0.4399709E 02	3	-0.4380255E 02	4	-0.4546309E 02
5	-0.4712364E 02	6	-0.4638564E 02	7	-0.4588194E 02	8	-0.4537836E 02
9	-0.4487460E 02	10	-0.4512508E 02	11	-0.4463634E 02	12	-0.4230336E 02
13	-0.3997021E 02	14	-0.3807492E 02	15	-0.3850592E 02	16	-0.5096230E 02
17	-0.5084869E 02	18	-0.5073520E 02	19	-0.5061043E 02	20	-0.5043391E 02
21	-0.5025737E 02	22	-0.5008078E 02	23	-0.4988054E 02	24	-0.4967865E 02
25	-0.4947662E 02	26	0.1257971E 02	27	0.1156945E 02	28	0.1064094E 02
29	0.9747601E 01	30	0.8857703E 01	31	0.9560899E 01	32	0.5922699E-01
33	0.5020859E 01	34	0.7020608E 01	35	0.6747023E 01	36	0.6332528E 01
37	0.5617196E 01	38	0.2694098E 01	39	-0.1458354E 01	40	-0.4112986E 01
41	-0.1501146E 01	42	0.1083861E 02	43	0.1452299E 02	44	0.1681815E 02
45	0.1618147E 02	46	0.1308310E 02	47	0.1042656E 02	48	0.7911580E 01
49	0.8854174E 01	50	0.1118453E 02	51	0.6430694E 01	52	0.3581647E 01
53	0.7326275E 00	54	-0.1987335E 01	55	-0.3005142E 01	56	-0.3782299E 01
57	-0.6369537E 01	58	-0.8450432E 01	59	-0.1053133E 02	60	-0.1261234E 02
61	-0.1353581E 02	62	-0.1672888E 02	63	-0.1731836E 02	64	-0.1792444E 02
65	-0.1853061E 02	66	-0.1913669E 02	67	-0.1974287E 02	68	-0.2019997E 02
69	-0.1976271E 02	70	-0.1932545E 02	71	-0.1888817E 02	72	-0.1845096E 02
73	-0.1798198E 02	74	-0.1752245E 02	75	-0.1704463E 02	76	-0.1656682E 02
77	-0.1608897E 02	78	-0.1561114E 02	79	-0.1513330E 02	80	-0.1465552E 02
81	-0.1417754E 02	82	-0.1369973E 02	83	-0.1322192E 02	84	-0.1274402E 02
85	-0.1226619E 02	86	-0.1178836E 02	87	-0.1131052E 02	88	-0.1083266E 02
89	-0.1105416E 02	90	-0.1336581E 02	91	-0.6785039E 02	92	-0.6784502E 02
93	-0.6783957E 02	94	-0.6783420E 02	95	-0.6782874E 02	96	-0.6782338E 02
97	-0.6781786E 02	98	-0.6781248E 02	99	-0.6780701E 02	100	-0.6780159E 02
101	-0.5594650E 01	102	-0.5353465E 01	103	-0.5112233E 01	104	-0.4871122E 01
105	-0.4630578E 01	106	-0.4389922E 01	107	-0.2112233E 02	108	-0.2016216E 02
109	-0.1920195E 02	110	-0.1824170E 02	111	-0.1728149E 02	112	-0.1632121E 02
113	-0.1536091E 02	114	-0.1440063E 02	115	-0.1511460E 02	116	-0.1582753E 02
117	-0.1654030E 02	118	-0.1725314E 02	119	-0.1796605E 02	120	-0.1774898E 02
121	-0.2570987E 02	122	-0.4080232E 02	123	-0.4175459E 02	124	-0.4270453E 02
125	-0.4365424E 02	126	-0.4460413E 02	127	-0.4541019E 02	128	-0.4478146E 02
129	-0.4861197E 02	130	-0.5224924E 02	131	-0.5803378E 02	132	-0.6354755E 02
133	-0.6727911E 02	134	-0.6833910E 02	135	-0.6939905E 02	136	-0.6920015E 02
137	-0.6900124E 02	138	-0.6880238E 02	139	-0.5748453E 02	140	-0.5728539E 02
141	-0.6513737E 02	142	-0.6410930E 02	143	-0.6312778E 02	144	-0.6226219E 02
145	-0.6139658E 02	146	-0.6053101E 02	147	-0.5966545E 02	148	-0.5879987E 02
149	-0.5793428E 02	150	-0.5706873E 02	151	-0.5680908E 02	152	-0.5663605E 02
153	-0.5646278E 02	154	-0.5648767E 02	155	-0.5671059E 02	156	-0.5693335E 02
157	-0.5715614E 02	158	-0.5737912E 02	159	-0.5760185E 02	160	-0.5782462E 02
161	-0.5804750E 02	162	-0.5827037E 02	163	-0.5849316E 02	164	-0.5871599E 02
165	-0.5920908E 02	166	-0.5980511E 02	167	-0.5982883E 02	168	-0.5985258E 02
169	-0.5987633E 02	170	-0.5990005E 02	171	0.3088055E 02	172	0.4009312E 02
173	0.3960297E 02	174	0.3911263E 02	175	0.3862250E 02	176	0.3813261E 02
177	0.3764232E 02	178	0.3715204E 02	179	0.3666168E 02	180	0.3617137E 02
181	0.3568100E 02	182	0.3519096E 02	183	0.3470076E 02	184	0.3421062E 02
185	0.3372122E 02	186	0.3323195E 02	187	0.3274258E 02	188	0.1136013E 02
189	0.1087016E 02	190	0.1249387E 02	191	0.7595470E 02	192	0.7614105E 02
193	0.7632660E 02	194	0.7651295E 02	195	0.7669846E 02	196	0.7688481E 02
197	0.7707031E 02	198	0.7725664E 02	199	0.7744298E 02	200	0.7762849E 02

TABLE - 9
DETECTION STATISTIC FOR CLASSIFICATION OF ENGINE OIL PROBLEM
CONTINUED

HOL	DETECTION STAT	HOL	DETECTION STAT	HOL	DETECTION STAT	HOL	DETECTION STAT
201	0.7781483E 02	202	0.7800041E 02	203	0.7818669E 02	204	0.7837225E 02
205	0.7855859E 02	206	0.7874406E 02	207	0.7893037E 02	208	0.7911676E 02
209	0.7850928E 02	210	0.7790109E 02	211	0.7729291E 02	212	0.7668423E 02
213	0.7607605E 02	214	0.7546782E 02	215	0.7485913E 02	216	0.6865387E 02
217	0.6838640E 02	218	0.6811887E 02	219	0.6785144E 02	220	0.6758394E 02
221	0.7191789E 02	222	0.6972888E 02	223	0.6754002E 02	224	0.6535114E 02
225	0.6316225E 02	226	0.6244119E 02	227	0.6269931E 02	228	0.6295744E 02
229	0.6321556E 02	230	0.6347371E 02	231	0.6373178E 02	232	0.6398994E 02
233	0.6424811E 02	234	0.6450612E 02	235	0.6476428E 02	236	0.6502235E 02
237	0.6528050E 02	238	0.6553873E 02	239	0.6553026E 02	240	0.6552260E 02
241	0.6551486E 02	242	0.6550717E 02	243	0.6549944E 02	244	0.6549168E 02
245	0.6548398E 02	246	0.6547626E 02	247	0.6546855E 02	248	0.6546086E 02
249	0.6545311E 02	250	0.6544539E 02	251	0.6543770E 02	252	0.6542998E 02
253	0.6542223E 02	254	0.6541454E 02	255	0.6540678E 02	256	0.6539906E 02
257	0.6539137E 02	258	0.6538365E 02	259	0.6537595E 02	260	0.6536816E 02
261	-0.5651573E 02	262	-0.5642024E 02	263	-0.5632478E 02	264	-0.5622928E 02
265	-0.5613382E 02	266	-0.5603835E 02	267	-0.5594284E 02	268	-0.5584746E 02
269	-0.5574092E 02	270	-0.5563036E 02	271	-0.5551979E 02	272	-0.5540923E 02
273	-0.5529854E 02	274	-0.5518799E 02	275	-0.5507741E 02		

FIGURE - 23 RELATIVE IMPORTANCE VECTOR FOR ENGINE OIL PROBLEM CLASSIFIER (8)

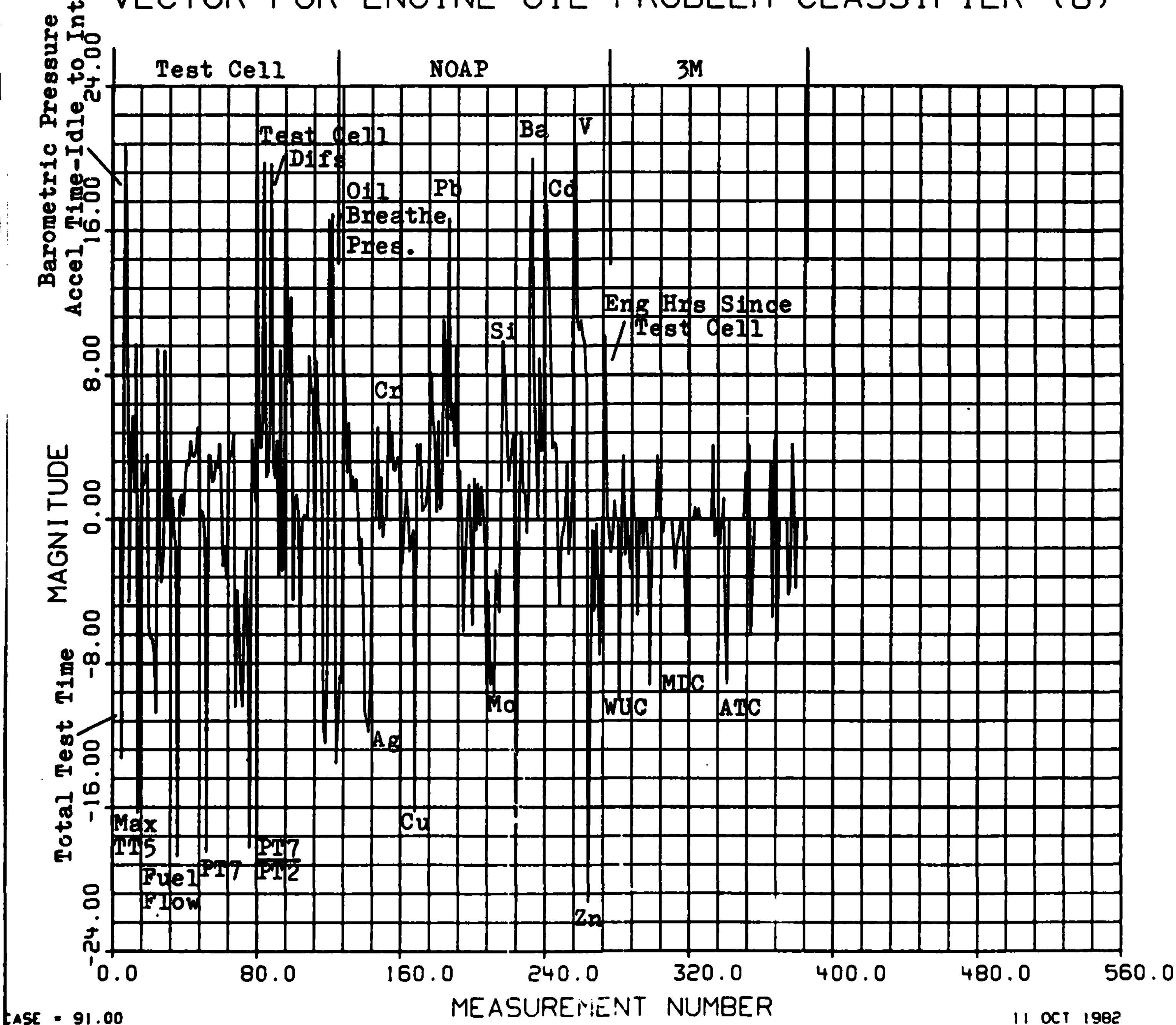


TABLE - 10

RELATIVE IMPORTANCE OF EACH MEASUREMENT FOR CLASSIFING ENGINE OIL PROBLEM (8)

MEAS	REL IMPORTANCE	MEAS	REL IMPORTANCE	MEAS	REL IMPORTANCE	MEAS	REL IMPORTANCE
1	0.1708716E-01	2	0.0	3	0.9981477E-01	4	0.0
5	-0.1327353E 02	6	0.5231941E 01	7	0.2083905E 02	8	0.1660902E 02
9	-0.4599689E 01	10	0.3876787E 01	11	0.5731088E 01	12	0.1505355E 01
13	0.9697378E 01	14	-0.1633542E 02	15	-0.2466566E 01	16	0.2531926E 01
17	0.1887396E 01	18	0.2319975E 01	19	0.3611209E 01	20	-0.5972656E 01
21	-0.6582720E 01	22	-0.6681767E 01	23	-0.7533530E 01	24	-0.1077086E 02
25	0.9421543E 01	26	-0.1704132E 01	27	-0.3500730E 01	28	-0.2107568E 01
29	0.9348791E 01	30	-0.5566525E-01	31	0.3230833E 01	32	-0.1446351E 01
33	0.1156534E 01	34	-0.6895745E 00	35	-0.1631311E 01	36	-0.1872023E 02
37	0.1079762E 01	38	0.1371016E 01	39	0.2015879E 00	40	0.2239396E 01
41	0.3277232E 01	42	0.2993741E 01	43	0.4343692E 01	44	0.3515962E 01
45	0.3453879E 01	46	0.3991420E 01	47	0.5110133E 01	48	-0.2423885E 00
49	0.4764525E 00	50	0.3572313E 00	51	-0.1263283E 01	52	-0.1848952E 02
53	0.3568098E 01	54	0.3506758E 01	55	0.2050207E 01	56	0.2185347E 01
57	0.3249122E 01	58	0.2833197E 01	59	0.4178794E 01	60	0.1919448E 01
61	-0.2597845E 01	62	-0.1498322E 01	63	-0.3292877E 01	64	0.3297016E 01
65	0.3444878E 01	66	0.3836926E 01	67	0.4809642E 01	68	-0.1042078E 02
69	-0.3928576E 01	70	-0.5431447E 01	71	-0.9716269E 01	72	-0.1040285E 02
73	-0.4408094E 01	74	-0.1593315E 01	75	-0.7813820E 01	76	-0.1824554E 02
77	0.4418269E 01	78	0.3233585E 01	79	0.9987410E 00	80	0.1903036E 02
81	0.6090330E 01	82	0.3930890E 01	83	0.5211027E 01	84	0.1976137E 02
85	0.2327701E 01	86	0.2589579E 01	87	0.4880867E 01	88	0.1968520E 02
89	0.2927450E 01	90	0.2299007E 01	91	0.4373613E 01	92	-0.3154135E 01
93	0.9342192E 01	94	-0.2868487E 01	95	-0.2287587E 01	96	0.2023883E 02
97	0.1243610E 02	98	0.7582270E 01	99	0.1227656E 02	100	-0.4481667E 01
101	0.1102430E 01	102	0.1374022E 01	103	0.2304264E 00	104	-0.7985203E 01
105	-0.2110197E 00	106	0.2772326E 00	107	0.1169280E 00	108	0.3630881E-01
109	0.9015286E 01	110	0.7005116E 01	111	0.7234431E 01	112	-0.3356195E 01
113	0.8761992E 01	114	0.5738296E 01	115	0.4894577E 01	116	0.1577459E 01
117	-0.1173645E 02	118	-0.1245040E 02	119	-0.8439672E 01	120	0.1658870E 02
121	0.1009739E 02	122	0.1691042E 02	123	0.3336288E 01	124	-0.1355265E 02
125	-0.1152129E 02	126	-0.8689876E 01	127	-0.9037701E 01	128	0.9348660E 01
129	0.6598420E 01	130	0.2594640E 01	131	0.5355586E 01	132	0.1649183E 01
133	0.2396297E 01	134	0.1551441E 01	135	0.2257163E 01	136	0.5467241E 00
137	-0.2514482E 01	138	-0.1065969E 01	139	-0.4824002E 01	140	-0.1067568E 02
141	-0.1129963E 02	142	-0.1179667E 02	143	-0.9245122E 01	144	0.0
145	0.0	146	0.0	147	0.5107758E 01	148	-0.5211608E 00
149	0.2361656E 01	150	-0.9800714E 00	151	0.6776887E-01	152	0.0
153	0.6384144E 01	154	0.3172613E 01	155	0.4849918E 01	156	0.2697002E 01
157	0.2719304E 01	158	0.3435630E 01	159	0.3411662E 01	160	-0.2250030E 01
161	-0.2447617E 01	162	-0.1966653E 00	163	0.1547014E 01	164	0.4489539E 00
165	-0.1798178E 01	166	-0.1061596E 01	167	-0.5885090E 00	168	-0.1625867E 02
169	0.4166578E 01	170	0.3014155E 01	171	0.4188429E 01	172	0.4398465E 00
173	0.6436656E 00	174	0.7826783E 00	175	0.1873313E 01	176	0.3270420E 01
177	0.8150932E 01	178	0.5585330E 01	179	0.4328151E 01	180	0.4064558E 00
181	0.5433560E 01	182	0.5567901E 00	183	0.8507768E 00	184	0.1103059E 02
185	0.9724088E 01	186	0.3518648E 01	187	0.1665273E 02	188	0.5495894E 01
189	0.6325615E 01	190	0.4070928E 01	191	0.9449975E 01	192	0.9018546E-01
193	0.2711521E 01	194	0.1093399E 00	195	-0.6225745E 01	196	-0.2144470E 01
197	0.2427573E 00	198	0.1933781E 01	199	-0.6558689E 00	200	-0.5855515E 01

TABLE - 10
RELATIVE IMPORTANCE OF EACH MEASUREMENT FOR CLASSIFING ENGINE OIL PROBLEM (8)
CONTINUED

MEAS	REL, IMPORTANCE	MEAS	REL IMPORTANCE	MEAS	REL IMPORTANCE	MEAS	REL IMPORTANCE
201	0.2271880E 01	202	-0.6072969E 00	203	0.1981501E 01	204	-0.3253478E 00
205	0.1828316E 01	206	0.3230826E 00	207	-0.1585448E 01	208	-0.1034432E 02
209	-0.3984319E 01	210	-0.9179000E 01	211	-0.7975349E 01	212	-0.9855249E 01
213	-0.2818507E 01	214	-0.3768105E 01	215	-0.5143890E 01	216	0.2854557E 01
217	0.9876358E 01	218	0.7995544E 01	219	0.4672799E 01	220	0.2157086E 01
221	0.3193971E 01	222	0.4423285E 01	223	0.4752962E 01	224	-0.2344547E 02
225	-0.8156336E 01	226	0.1835861E 01	227	0.4877690E 01	228	0.1486761E 01
229	0.1487247E 01	230	-0.7388483E 00	231	0.1529655E 01	232	0.1586833E 02
233	0.1998611E 02	234	0.7535907E 01	235	0.3860134E 01	236	-0.4157930E-01
237	0.8909622E 01	238	0.3781782E 01	239	0.4312179E 01	240	0.1411208E 02
241	0.1742984E 02	242	0.1383129E 02	243	0.1077316E 02	244	0.3940552E 01
245	0.4286760E 01	246	0.4177462E 01	247	-0.1333949E 01	248	-0.4701575E 01
249	-0.1130825E 01	250	-0.5656132E 00	251	0.1018335E 00	252	0.3075089E 01
253	-0.1917751E 01	254	-0.8387217E 00	255	0.2173745E 01	256	0.2078156E 02
257	0.2071355E 02	258	0.1093999E 02	259	0.1046851E 02	260	0.1102424E 02
261	0.1014806E 02	262	0.9774412E 01	263	0.7464877E 01	264	-0.2126799E 02
265	-0.1331017E 02	266	-0.6063534E 00	267	-0.5054341E 01	268	-0.2610070E 00
269	-0.2976630E 01	270	-0.7531023E 01	271	-0.1516469E 01	272	0.1761241E 01
273	0.1014161E 02	274	0.4330349E 00	275	-0.4941651E 00	276	-0.1829984E 01
277	-0.1096126E 01	278	0.1022642E 01	279	0.0	280	0.0
281	-0.1005101E 02	282	0.0	283	0.3540853E 01	284	-0.1971309E 01
285	0.0	286	-0.1489588E 01	287	-0.2752574E 01	288	0.3839211E 01
289	0.0	290	0.0	291	-0.5314449E 01	292	0.0
293	0.0	294	-0.1489588E 01	295	0.0	296	0.0
297	-0.2544846E 01	298	-0.9204114E 01	299	0.0	300	0.0
301	0.0	302	0.3540853E 01	303	0.8639866E-01	304	0.0
305	-0.7399948E 00	306	0.0	307	0.0	308	0.0
309	0.0	310	0.0	311	-0.1489588E 01	312	-0.2752090E 01
313	-0.1278911E 01	314	-0.9592043E 00	315	0.0	316	0.0
317	-0.2391494E 01	318	-0.6452022E 01	319	0.0	320	0.0
321	0.0	322	0.0	323	0.6530114E 00	324	0.0
325	0.6127911E 00	326	0.0	327	0.0	328	0.0
329	0.0	330	0.0	331	0.0	332	0.0
333	0.4119658E 01	334	-0.9592043E 00	335	0.0	336	0.0
337	-0.1364345E 01	338	0.0	339	0.1174122E 01	340	-0.6452022E 01
341	-0.9154174E 01	342	0.0	343	0.0	344	0.0
345	0.0	346	0.0	347	0.0	348	0.0
349	0.0	350	0.0	351	0.2571131E 01	352	0.0
353	0.4119658E 01	354	-0.6452022E 01	355	-0.4220631E 01	356	0.0
357	0.0	358	0.0	359	0.0	360	0.0
361	0.0	362	0.0	363	0.0	364	0.0
365	0.3176150E 01	366	-0.5459530E 01	367	0.4178589E 01	368	0.4495828E 01
369	-0.6767488E 01	370	0.0	371	0.0	372	0.0
373	0.0	374	0.0	375	-0.4208036E 01	376	-0.3742008E 01
377	0.4178589E 01	378	0.1454979E 01	379	-0.3821950E 01	380	0.0
381	0.0	382	0.0	383	0.0	384	0.0
385	-0.1178470E 01						

Use of ADAPT Analysis Techniques for Failure Diagonsis

The techniques which we will discuss in this subsection have the same relation to the detection algorithms which we have discussed in the preceding subsections as the scatter plot incipient failure technique had to the incipient failure algorithms. That is, these techniques require an experienced mechanic/technician to examine detail results which have been processed to make the pertinent information more visible. They are intended as a supplement to the automated system and are available at negligible additional effort as part of the ADAPT processing. Once again, all of our performance estimates do not include performance that could be obtained as a result of making use of these capabilities which will be included in the system. The two approaches which can be used to assist in the diagnosis are examination of the scatter plot and creation of an appropriate relative importance vector.

The examination of the scatter plot is very similar to that which was discussed in Section 4.2 for incipient failure detection. The major difference would be that superimposed upon the scatter plot as shown in Figure 19 would be the identification of all other failures which have previously occurred in the history of that engine and appropriately adjusted failures which have occurred in other engines. Thus, by noting how the engine deviates from its normal position relative to how engines with other failures have deviated, one gets information which would be very useful in diagnosing the failure.

A second diagnostic tool which can be applied: 1) when the automated system detects an incipient failure and is unable to make a satisfactory diagnosis using either the specific

failure detector or the failure classifier, or 2) an unexplained deviation from the scatter plot is observed is analysis of the relative importance vector. To obtain the relative importance vector, an algorithm is developed to separate the case or cases which exhibit the failure indication from all the normal cases of that engine and possibly other engines. When this algorithm is developed, its relative importance vector can be displayed and it will indicate which of the measurements were most responsible for the deviation from a healthy engine. This has proved very useful in a number of other applications and is described in considerable detail in a study[5] of a diagnostic system for the Saturn booster. The final report on that study describes this method in detail and presents an illustration of its use in determining failure modes in the Saturn booster.

4.4 ESTIMATING TIME TO FAILURE

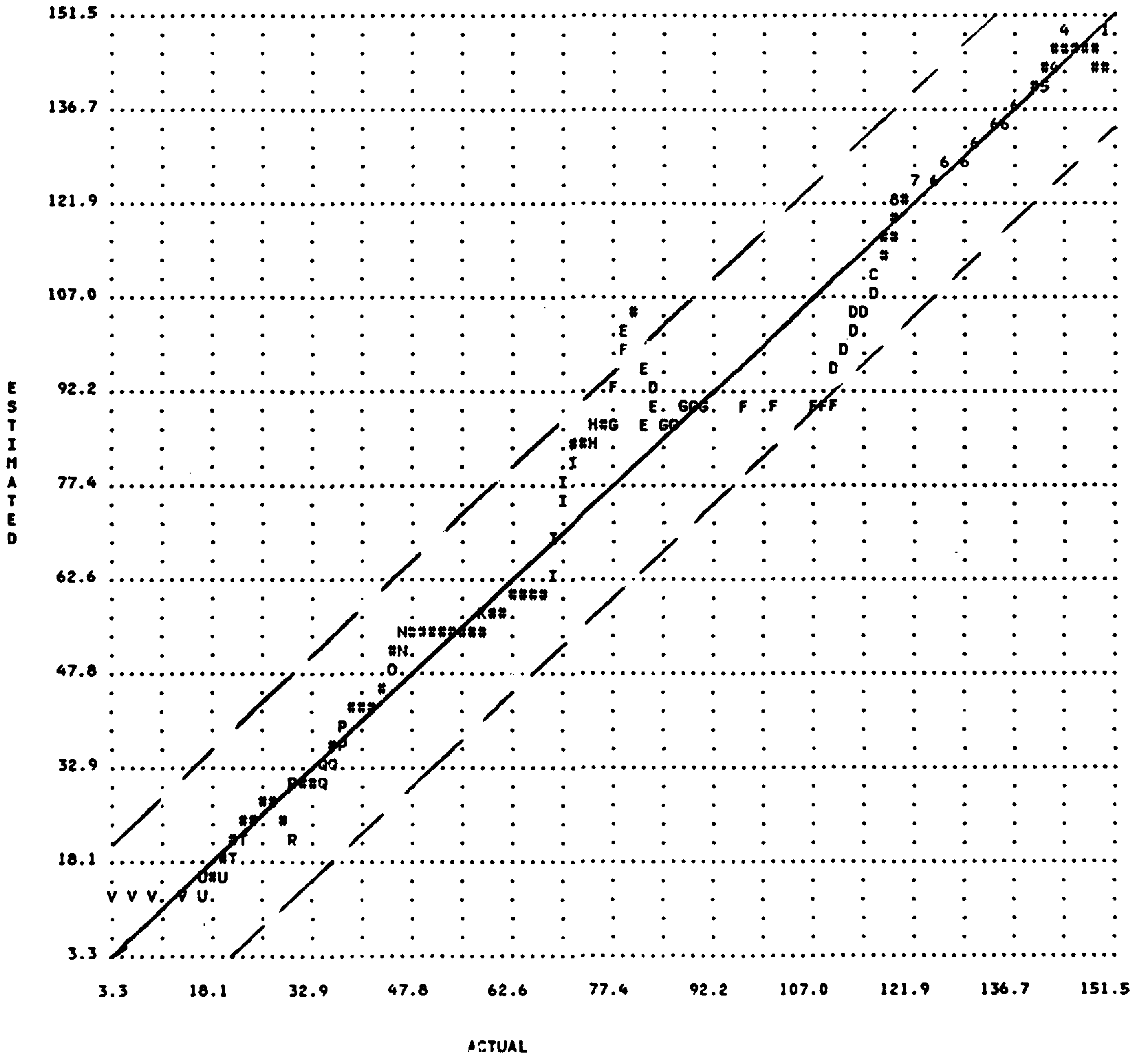
The final task which will be accomplished by the automated system, whenever it is possible, is to provide an estimate of the number of engine hours remaining before the failure is expected to occur. This is accomplished using a time to failure algorithm. This algorithm is derived for each failure mode for which sufficient experience is available. In the present set of data, the engine failure due to a clogged sump strainer provided a long history of the data prior to the occurrence of this failure. Thus, a regression equation was developed between the data history and the engine hours remaining to failure. This regression equation has an expected 3-Sigma error of 18 engine hours.

Figure 24 presents a plot of the results obtained by applying this regression equation using the group out independent test method of Lackenbrach[4]. The ordinate of this plot is the estimated time until the failure. The actual time is plotted along the abscissa. Thus, any points lying on the diagonal line dividing the figure into equal halves will represent a perfect estimate since the estimated and actual values are identical. The distance away from this diagonal line through the center of this figure is a measure of the size of the error. Two additional dash lines have been added

(5) Hunter, H.E.; "Implementation and Demonstration of ADAPT Empirical Analysis at KSC", ADAPT Report #76-3, June 1976.

FIGURE - 24

ESTIMATE ENGINE HOURS BEFORE CLOGGED SUMP STRAINER IN MAIN OIL PUMP
CASE 71 RHO=0.989 ERROR= 4.12E 00



to Figure 24 and are the lines representing a error of plus 18 hours and minus 18 hours, respectively. Points lying between these two lines have less than 18 hour errors in their prediction of the time to failure.

Figure 25 shows the relative importance vector for the time to failure of sump strainer in main oil pump. Since the test cell data does not vary over the time to failure, the test cell measurements will not contribute and the relative importance vector only shows the NOAP and 3M data. The least important elements were aluminum (Al) and vanadium (V). Copper (Cu), lead (Pb), molybdenum (Mo), manganese (Mn) and zinc (Zn) concentration increased as time to failure decreased, but magnesium, titanium, tin, and cadmium concentration decrease as time to failure decreases.

4.5 Comparison of Automated and Manual Test Cell Data

Since both manually and automatically recorded test cell were used in this study, it is desirable to determine if there is a significant difference between these two sets and if so, the expected impact on the results of this study. To accomplish this, an algorithm was developed separating the three engines for which the automated test cell data was used from the remaining 11 engines. The expected probability of error obtained was 0.1. This is significant, but not a strong enough separation to be expected to cause difficulties in the present study.

The probability of error of 0.1 is sufficiently strong to warrant a study of the differences between the two data sets. Thus, the relative importance vector was constructed and is shown in Figure 26. It is both interesting and important to note that the dominant difference is in the NOAP measurements and not the test cell. This suggests that very little of the difference is due to the method of recording the test cell data. The dominant difference is most likely to some other factor effecting these engines uniformly and only incidentally related to the test cell. For example, about a third of the observations are from the two engines for which early (and, therefore, manually recorded) data was available. Thus, in general, the NOAP data for the automatically recorded test cell cases is more recent data. Any improvements in the NOAP data acquisition and recording would thus become a marginally good discriminants. This explanation is also consistent with the data presented in Figure 26 which shows that for many of the elements the significant feature is the change (either positive or negative) over the most recent 75 hours. This is the behavior that would be

GURE 25 RELATIVE IMPORTANCE
TOR FOR TIME TO FAILURE ESTIMATE

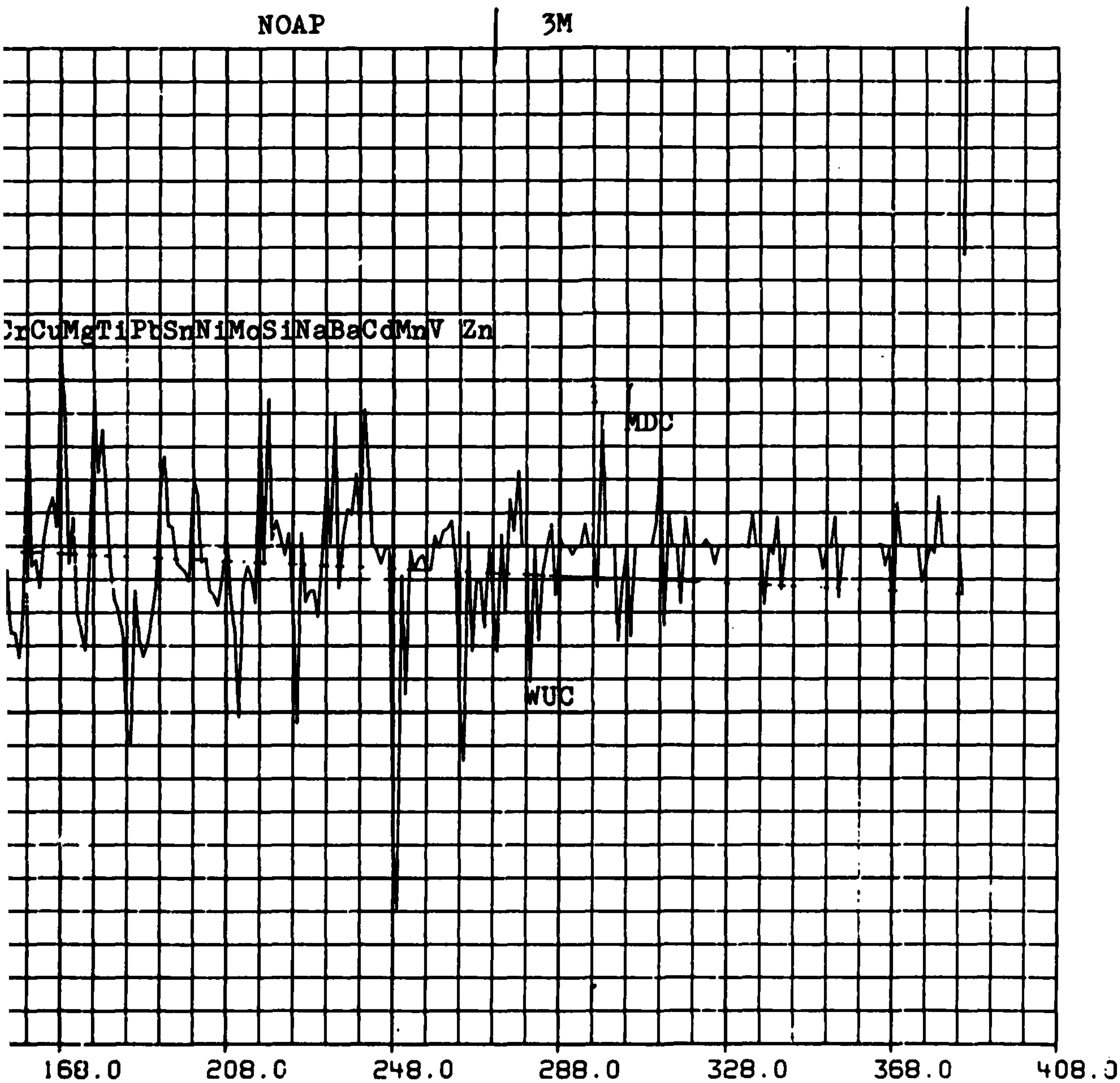


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TABLE 11
RELATIVE IMPORTANCE VECTOR FOR TIME TO FAILURE ESTIMATE

MEAS	REL IMPORTANCE	MEAS	REL IMPORTANCE	MEAS	REL IMPORTANCE	MEAS	REL IMPORTANCE
1	0.1811954E 02	2	0.0	3	0.3024832E 02	4	0.0
5	-0.2207857E 02	6	0.7134973E 01	7	-0.1971641E 01	8	-0.2326353E 02
9	-0.2275140E 02	10	0.2511470E 02	11	-0.2132210E 02	12	-0.2714983E 02
13	0.8708888E 01	14	0.2556085E 02	15	0.3311343E 02	16	0.5397070E 01
17	0.1029133E 02	18	0.8190779E 01	19	0.1011414E 02	20	-0.5144060E 02
21	-0.5649519E 02	22	-0.5497716E 02	23	-0.5537741E 02	24	-0.1213946E 02
25	-0.8255156E 01	26	0.1590917E 02	27	0.7236737E 00	28	-0.4768697E 02
29	-0.1112361E 02	30	-0.2102077E 02	31	-0.1879808E 02	32	-0.3098183E 02
33	-0.2501199E 02	34	-0.2438673E 02	35	-0.2689346E 02	36	0.1109906E 02
37	-0.3304419E 02	38	-0.3725731E 02	39	-0.4412831E 02	40	0.3473918E 02
41	0.2732307E 02	42	0.3327876E 02	43	0.3153551E 02	44	0.1390596E 02
45	0.4553671E 02	46	0.4269647E 02	47	0.4175151E 02	48	0.1975603E 02
49	0.4388660E 02	50	0.4388602E 02	51	0.4479907E 02	52	0.3373638E 01
53	0.3926891E 02	54	0.1624648E 02	55	0.1587686E 02	56	0.3435889E 02
57	0.2712988E 02	58	0.3277260E 02	59	0.3150589E 02	60	-0.2146735E 02
61	-0.5872766E 01	62	-0.1031424E 02	63	-0.1315983E 02	64	0.1297806E 02
65	0.4855981E 02	66	0.4414424E 02	67	0.4324596E 02	68	0.9972462E 01
69	0.2767566E 02	70	0.2097910E 02	71	0.2863246E 02	72	0.8075886E 01
73	0.7429203E 01	74	0.3880087E 02	75	0.2411200E 02	76	0.3086404E 01
77	0.5728101E 02	78	0.1879800E 02	79	0.1647873E 02	80	-0.1646494E 02
81	-0.7346181E 00	82	0.9931237E 01	83	0.1048442E 02	84	0.1719724E 01
85	0.3591031E 02	86	0.4282072E 02	87	0.3837354E 02	88	0.2425583E 02
89	0.2139992E 02	90	0.3102498E 02	91	0.3080017E 02	92	0.2906693E 01
93	-0.3238458E 02	94	0.2133072E 02	95	0.7984145E 01	96	0.1009389E 01
97	0.1539237E 02	98	0.3889493E 02	99	0.3201576E 02	100	0.1155224E 02
101	-0.3325113E 02	102	-0.3701300E 02	103	-0.4401697E 02	104	0.1580340E 02
105	0.1440086E 00	106	-0.2574954E 01	107	0.2327294E 01	108	-0.1105329E 02
109	-0.9679238E 01	110	-0.1730185E 02	111	-0.1554884E 02	112	-0.2744084E 02
113	-0.4742670E 01	114	0.1253045E 02	115	0.1482786E 02	116	-0.4092142E 01
117	-0.1346525E 02	118	-0.1632515E 02	119	-0.1378180E 02	120	-0.2210315E 02
121	0.1181895E 02	122	0.2674503E 01	123	0.2214327E 01	124	-0.9601659E 01
125	0.6283908E 00	126	0.1006909E 01	127	0.2321857E 01	128	-0.1876996E 02
129	0.1211239E 01	130	-0.2916342E 02	131	-0.4761097E 00	132	-0.2198848E 02
133	-0.2472729E 02	134	-0.2404926E 02	135	-0.1285520E 02	136	-0.1463058E 02
137	-0.1818951E 02	138	-0.2431472E 01	139	-0.1399133E 02	140	-0.2111284E 02
141	-0.2083104E 02	142	-0.4296099E 01	143	-0.1057266E 02	144	0.0
145	0.0	146	0.0	147	-0.1687626E 01	148	-0.7800862E 00
149	0.2118896E 01	150	0.1402496E 01	151	0.3101062E 00	152	0.0
153	-0.5246964E 01	154	-0.2250687E 02	155	-0.5785944E 01	156	-0.2106975E 02
157	-0.2099193E 02	158	-0.2700819E 02	159	-0.1623752E 02	160	0.3778711E 02
161	-0.4798971E 01	162	-0.3439010E 01	163	-0.1021889E 02	164	0.1370200E 01
165	0.8183815E 01	166	0.1176498E 02	167	0.4533921E 01	168	0.4982469E 02
169	0.3051796E 02	170	-0.4269599E 01	171	0.6792989E 01	172	-0.1550553E 02
173	-0.2077245E 02	174	-0.2517036E 02	175	-0.3481260E 01	176	0.3560121E 02
177	0.1782309E 02	178	0.2808128E 02	179	0.1103659E 02	180	-0.5167615E 01
181	-0.1281576E 02	182	-0.1567142E 02	183	-0.2138501E 02	184	-0.4421077E 02
185	-0.4728918E 02	186	-0.1067442E 02	187	-0.2247888E 02	188	-0.2669786E 02
189	-0.2350948E 02	190	-0.1770911E 02	191	-0.1037648E 02	192	0.1322395E 02
193	0.2168051E 02	194	0.4945058E 01	195	0.4646144E 01	196	-0.4018613E 01
197	-0.5198413E 01	198	-0.6124869E 01	199	-0.8457076E 01	200	0.1604269E 02

TABLE 11
RELATIVE IMPORTANCE VECTOR FOR TIME TO FAILURE ESTIMATE
CONTINUED

MEAS	REL IMPORTANCE	MEAS	REL IMPORTANCE	MEAS	REL IMPORTANCE	MEAS	REL IMPORTANCE
201	0.1242579E 02	202	-0.3940800E 01	203	-0.2934434E 01	204	-0.1069481E 02
205	-0.1193093E 02	206	-0.1441004E 02	207	-0.7281200E 01	208	0.4669232E 01
209	-0.1155753E 02	210	-0.2060773E 02	211	-0.4121910E 02	212	-0.948[illegible]249E 01
213	-0.4728569E 01	214	-0.7533773E 01	215	-0.1365840E 02	216	0.3335719E 02
217	-0.4364468E 01	218	0.3549054E 02	219	0.1473612E 01	220	0.6121931E 01
221	0.2398077E 01	222	-0.2244514E 01	223	0.3102565E 01	224	-0.1530519E 02
225	-0.4270341E 02	226	0.3147703E 01	227	-0.1344484E 02	228	-0.1083613E 02
229	-0.1066467E 02	230	-0.1705042E 02	231	-0.1657433E 01	232	0.1676251E 02
233	0.7881571E 00	234	0.3224231E 02	235	-0.1016324E 02	236	0.1963529E 01
237	0.8951687E 01	238	0.7483651E 01	239	0.1744193E 02	240	0.3988525E 01
241	0.3301645E 02	242	0.1934474E 02	243	0.5388067E 00	244	-0.1132357E 01
245	-0.4226152E 01	246	-0.5253316E 00	247	-0.4460971E 00	248	-0.6885822E 02
249	-0.8731750E 02	250	-0.7052401E 01	251	-0.3562723E 02	252	-0.9381121E 00
253	-0.5717484E 01	254	-0.2960257E 01	255	-0.2131450E 01	256	-0.5702600E 01
257	-0.5467925E 01	258	0.2457834E 01	259	-0.4495196E 00	260	0.3606641E 01
261	0.4198183E 01	262	0.6154981E 01	263	-0.3655245E 01	264	-0.3953470E 02
265	-0.5179640E 02	266	0.3421599E 01	267	-0.2521307E 02	268	-0.8457817E 01
269	-0.8432563E 01	270	-0.1948293E 02	271	-0.6772009E 00	272	-0.1186386E 02
273	-0.2539018E 02	274	0.2782336E 01	275	-0.1565571E 02	276	0.1127676E 02
277	0.3666498E 01	278	0.1814375E 02	279	0.0	280	0.0
281	-0.3268866E 02	282	0.0	283	-0.2275354E 02	284	-0.5902121E 01
285	0.0	286	0.5367010E 01	287	-0.1174078E 02	288	0.2311271E 01
289	0.0	290	0.0	291	-0.2031182E 01	292	0.0
293	0.0	294	0.5367010E 01	295	0.0	296	0.0
297	-0.9834982E 01	298	0.3157155E 02	299	0.0	300	0.0
301	0.0	302	-0.2275354E 02	303	-0.9256527E 01	304	0.0
305	-0.2178391E 02	306	0.0	307	0.0	308	0.0
309	0.0	310	0.0	311	0.5367010E 01	312	0.2453999E 02
313	-0.1922025E 02	314	0.7794013E 01	315	0.0	316	0.0
317	-0.1380434E 02	318	0.7031548E 01	319	0.0	320	0.0
321	0.0	322	0.0	323	0.1509027E 01	324	0.0
325	-0.441044[illegible] 01	326	0.0	327	0.0	328	0.0
329	0.0	330	0.0	331	0.0	332	0.0
333	-0.4665084E 00	334	0.7794013E 01	335	0.0	336	0.0
337	-0.1401231E 02	338	0.0	339	-0.2048999E 01	340	0.7031548E 01
341	-0.1043013E 02	342	0.0	343	0.0	344	0.0
345	0.0	346	0.0	347	0.0	348	0.0
349	0.0	350	0.0	351	-0.[illegible]20663E 01	352	0.0
353	-0.4665084E 00	354	0.7031548E 01	355	-0.1240313E 02	356	0.0
357	0.0	358	0.0	359	0.0	360	0.0
361	0.0	362	0.0	363	0.0	364	0.0
365	0.5247098E 00	366	-0.4770487E 01	367	-0.1968421E 00	368	-0.2455171E 02
369	0.1034956E 02	370	0.0	371	0.0	372	0.0
373	0.0	374	0.0	375	-0.8810437E 01	376	-0.4273425E 01
377	-0.1968421E 00	378	-0.179[illegible]81E 01	379	0.1193205E 02	380	0.0
381	0.0	382	0.0	383	0.0	384	0.0
385	-0.1157796E 02						

FIGURE – 26 RELATIVE IMPORTANCE VECTOR FOR SEPERATION OF AUTOMATED VS. MANUAL TEST CELL

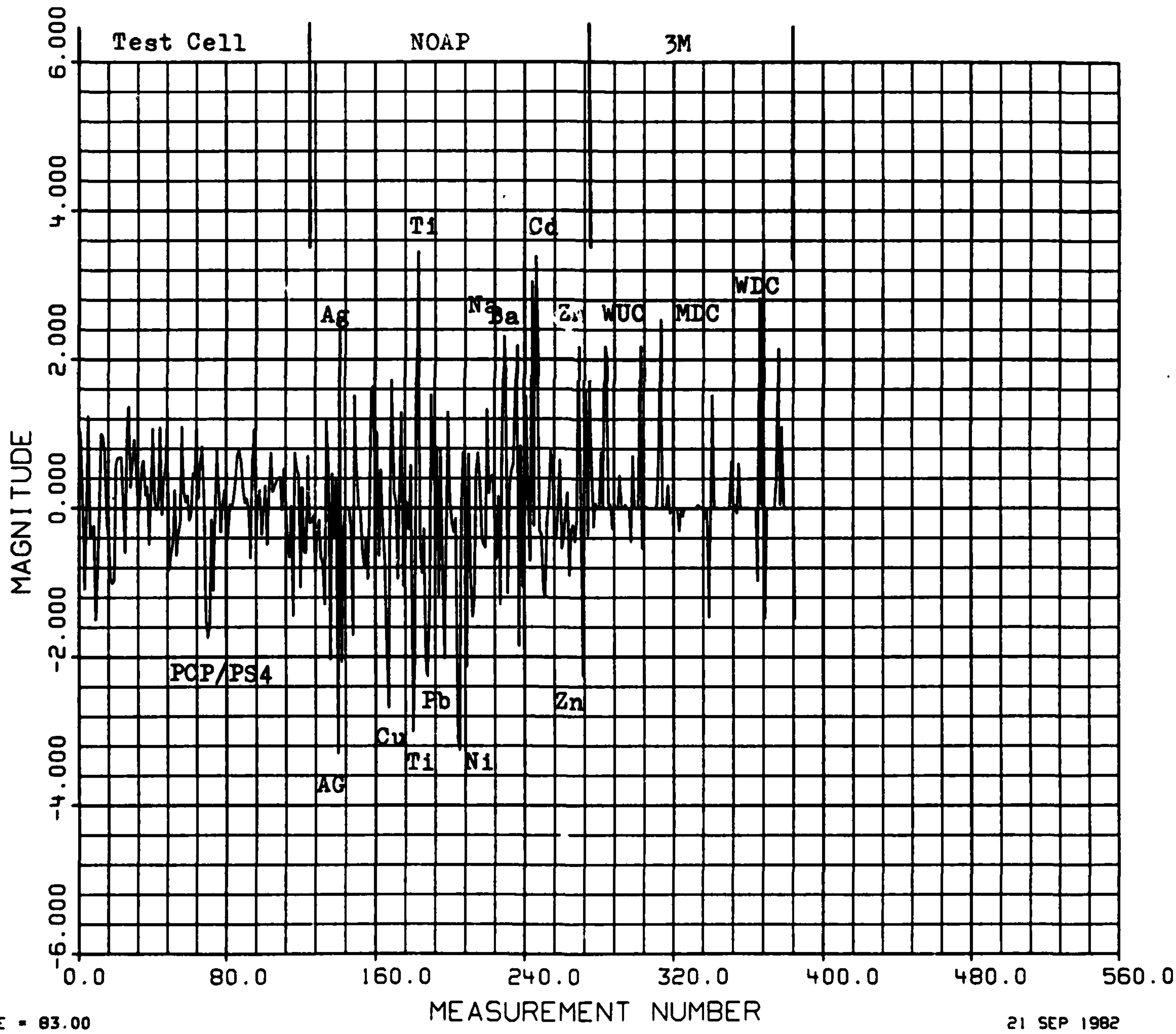

TABLE 12

RELATIVE IMPORTANCE VECTOR FOR SEPERATION OF AUTOMATED VS. MANUAL TEST CELL

MEAS	REL IMPORTANCE	MEAS	REL IMPORTANCE	MEAS	REL IMPORTANCE	MEAS	REL IMPORTANCE
1	0.1018085E 01	2	0.0	3	-0.1089779E 01	4	0.0
5	0.1246382E 01	6	-0.3721313E 00	7	-0.3763975E 00	8	-0.2357730E 00
9	-0.1505960E 01	10	-0.8697131E 00	11	-0.7058561E-02	12	0.1003872E 01
13	0.9687006E 00	14	0.7296810E 00	15	-0.2096103E 00	16	-0.3867985E 00
17	-0.9405985E 00	18	-0.1014250E 01	19	-0.9794769E 00	20	0.5848576E 00
21	0.6723406E 00	22	0.6815616E 00	23	0.6859415E 00	24	-0.3787015E-01
25	-0.5976703E 00	26	0.9817330E 00	27	0.1365042E 01	28	0.2816179E 00
29	0.6093217E 00	30	0.9223944E 00	31	0.5164803E 00	32	-0.7833207E-01
33	0.1129186E 00	34	0.5569226E 00	35	0.6395934E 00	36	0.1750003E 00
37	0.2920814E 00	38	-0.4887795E 00	39	0.2259300E 00	40	0.1070677E 01
41	0.1149422E 00	42	-0.2331235E-01	43	0.6949985E-01	44	0.1089698E 01
45	-0.8702016E-01	46	0.3703020E 00	47	0.5503922E 00	48	0.1194916E 01
49	-0.8345086E 00	50	-0.6399178E 00	51	-0.4547102E 00	52	0.2453933E 00
53	-0.6395231E 00	54	-0.3462794E 00	55	-0.1877664E 00	56	0.1097836E 01
57	0.2114109E 00	58	0.7903212E-01	59	0.1732534E 00	60	-0.1708778E 00
61	-0.9517187E-01	62	0.4733251E 00	63	0.4294723E 00	64	0.1074327E 01
65	0.1330135E 00	66	0.6072890E 00	67	0.8367351E 00	68	0.1642430E 00
69	-0.1500145E 01	70	-0.1745461E 01	71	-0.1564552E 01	72	-0.1504921E 00
73	-0.1109724E 01	74	-0.9440714E-01	75	0.8007820E 00	76	0.2560797E 00
77	-0.3223236E 00	78	0.7860243E-01	79	0.2485110E 00	80	-0.4704635E 00
81	-0.3564538E 00	82	0.5625586E-01	83	0.3590429E-02	84	0.1417637E 00
85	0.3953172E 00	86	0.7165062E 00	87	0.7941809E 00	88	0.6201147E 00
89	0.2815247E 00	90	0.6689376E-01	91	0.1310009E 00	92	-0.2671614E-01
93	-0.6711054E 00	94	0.6429899E 00	95	0.1060694E 01	96	-0.3902369E 00
97	0.1319414E 00	98	0.2436889E 00	99	-0.3557938E 00	100	-0.2259531E-01
101	0.3030061E 00	102	-0.4918456E 00	103	0.2229036E 00	104	0.7482947E 00
105	0.2175782E 00	106	0.2948643E 00	107	0.3575197E 00	108	0.4041923E 00
109	0.4200033E 00	110	-0.2841466E-01	111	0.5309823E 00	112	0.7595253E-01
113	-0.3946757E 00	114	-0.6624296E 00	115	0.3113265E-01	116	-0.1448764E 01
117	0.7457741E 00	118	0.5261017E 00	119	0.4565759E 00	120	-0.1066514E 01
121	0.2849959E 00	122	-0.5938578E 00	123	-0.5996774E 00	124	0.7033874E 00
125	-0.2070535E 00	126	-0.1835868E 00	127	-0.9886330E-01	128	-0.8479465E 00
129	-0.3439504E 00	130	-0.1575369E 00	131	-0.6644541E 00	132	-0.7496418E 00
133	-0.1294952E 01	134	0.1176556E 01	135	0.6796265E 00	136	-0.2041567E 01
137	0.4661023E 00	138	-0.3668765E 00	139	0.4101796E 00	140	-0.3301781E 01
141	0.2492840E 01	142	-0.2071362E 01	143	-0.2662153E 00	144	0.0
145	0.0	146	0.0	147	-0.2519156E 00	148	-0.1706675E 01
149	0.1515148E 01	150	0.5784603E 00	151	-0.3019676E-02	152	0.0
153	-0.5672472E 00	154	-0.7795215E 00	155	-0.4130157E 00	156	-0.9545544E 00
157	0.1647398E 00	158	0.1612987E 01	159	0.1637140E 01	160	-0.3573328E-01
161	0.1022497E 01	162	-0.6450409E 00	163	0.5179466E 00	164	-0.2578800E 00
165	-0.6739447E 00	166	-0.1982259E 01	167	-0.2688988E 01	168	0.4510049E 00
169	0.1721919E 01	170	0.2096299E 00	171	0.9237427E-01	172	-0.9505637E 00
173	0.3267555E 00	174	0.1288099E 01	175	-0.1051185E 01	176	-0.5093591E 00
177	0.7618421E-01	178	-0.2881049E 00	179	0.5797990E 00	180	-0.3009304E 01
181	-0.2188746E 01	182	0.1713390E 01	183	0.3447759E 01	184	-0.5283892E 00
185	-0.8759008E 00	186	-0.2757357E 00	187	-0.2193084E 01	188	-0.2266396E 01
189	-0.1246584E 01	190	0.1525523E 01	191	0.4323676E 00	192	0.2796764E 00
193	0.8194684E 00	194	-0.1165831E 01	195	0.8018109E 00	196	-0.8635628E 00
197	-0.2028993E 01	198	-0.2471510E 00	199	0.1294840E 01	200	0.6394655E-01

TABLE 12
RELATIVE IMPORTANCE VECTOR FOR SEPERATION OF AUTOMATED VS. MANUAL TEST CELL
CONTINUED

MEAS	REL IMPORTANCE	MEAS	REL IMPORTANCE	MEAS	REL IMPORTANCE	MEAS	REL IMPORTANCE
201	-0.2081120E 00	202	-0.3258350E 00	203	-0.1368968E 00	204	-0.3126664E 01
205	-0.3259713E 01	206	-0.2023207E-01	207	0.7548226E 00	208	0.7526028E 00
209	-0.2132229E 01	210	0.7317746E 00	211	-0.8883212E 00	212	-0.1465303E 01
213	-0.1238606E 01	214	0.4934839E 00	215	0.7470947E 00	216	0.3994610E 00
217	-0.4070061E 00	218	-0.4892903E 00	219	-0.5322373E 00	220	0.1331966E 01
221	0.2001110E 00	222	0.4258492E 00	223	0.4458765E 00	224	-0.1708074E 00
225	-0.6892467E 00	226	0.1613944E 00	227	-0.1299676E 01	228	0.8178920E 00
229	0.2312072E 01	230	0.1740284E 01	231	-0.1147779E 01	232	0.2889165E 00
233	0.5046159E 00	234	0.5874128E 00	235	0.1381331E 01	236	0.2187643E 01
237	-0.1859010E 01	238	0.8441610E 00	239	-0.1064203E 01	240	-0.3272750E 00
241	0.1505892E 01	242	0.3613245E-03	243	-0.7066644E 00	244	0.3046526E 01
245	-0.2400309E 00	246	0.3385388E 01	247	0.2494578E 01	248	-0.3063068E 00
249	-0.3411261E 00	250	-0.1107679E 01	251	-0.1185490E 01	252	-0.1612706E 00
253	0.8463031E-01	254	0.7749497E 00	255	0.6085081E 00	256	-0.3986628E 00
257	-0.3727073E 00	258	0.2928561E-01	259	0.6478235E 00	260	-0.5436526E 00
261	-0.3817582E 00	262	-0.6634004E-02	263	0.2172058E 00	264	-0.9072200E 00
265	-0.2881098E 00	266	-0.2212836E 00	267	-0.4516054E 00	268	-0.1661353E 00
269	0.2175265E 01	270	0.4804091E 00	271	-0.2253542E 01	272	0.3783053E 00
273	0.1590540E 01	274	-0.3627958E 00	275	0.1718975E 01	276	0.5798674E 00
277	-0.2528992E 00	278	0.6981200E-01	279	0.0	280	0.0
281	0.7568367E 00	282	0.0	283	0.2180402E 01	284	0.2032288E 01
285	0.0	286	0.5619595E-01	287	-0.2712603E 00	288	0.5699829E-01
289	0.0	290	0.0	291	0.4461870E 00	292	0.0
293	0.0	294	0.5619595E-01	295	0.0	296	0.0
297	-0.4516575E 00	298	0.7069039E 00	299	0.0	300	0.0
301	0.0	302	0.2180402E 01	303	-0.5387750E 00	304	0.0
305	0.2995598E-01	306	0.0	307	0.0	308	0.0
309	0.0	310	0.0	311	0.5619595E-01	312	0.7769780E 00
313	0.2540762E 01	314	0.3256287E-01	315	0.0	316	0.0
317	0.3120646E 00	318	-0.7007414E-01	319	0.0	320	0.0
321	0.0	322	0.0	323	-0.3129938E 00	324	0.0
325	-0.1132333E 00	326	0.0	327	0.0	328	0.0
329	0.0	330	0.0	331	0.0	332	0.0
333	0.4789465E-01	334	0.3256287E-01	335	0.0	336	0.0
337	-0.1348047E 00	338	0.0	339	-0.1467619E 01	340	-0.7007414E-01
341	0.1521866E 01	342	0.0	343	0.0	344	0.0
345	0.0	346	0.0	347	0.0	348	0.0
349	0.0	350	0.0	351	0.6308983E 00	352	0.0
353	0.4789465E-01	354	-0.7007414E-01	355	0.6078094E 00	356	0.0
357	0.0	358	0.0	359	0.0	360	0.0
361	0.0	362	0.0	363	0.0	364	0.0
365	-0.9781681E 00	366	0.2826782E 01	367	0.4526872E-01	368	0.3277752E 01
369	-0.1481498E 01	370	0.0	371	0.0	372	0.0
373	0.0	374	0.0	375	0.3785250E 00	376	0.2148601E 01
377	0.4526872E-01	378	0.1097348E 01	379	0.3401626E-01	380	0.0
381	0.0	382	0.0	383	0.0	384	0.0
385	-0.1486161E 01						

expected as new oil adjusts to an equilibrium. A larger and more complete sample of engines would eliminate this discriminant.

A second feature of importance is that the NOAP components most important to the separation of manually vs automatically recorded data are not important to any other classification studied. This suggests that these differences will have a negligible effect on the present study.

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APPENDIX A

REVIEW OF ADAPT APPROACH TO EMPIRICAL DATA ANALYSIS

SEPTEMBER 1982

This attachment will present the detail information which defines the ADAPT approach to empirical data analysis. This approach is based on the concept that empirical data analysis should be preceded by transforming the data from the original data space to a more efficient analysis space. This more efficient analysis space is defined as that space which requires the least number of numbers to represent a given amount of information in the original data set. It can be shown that this space is simply the eigenvector space and the transformation required is the eigenvector or the Karhunen-Loeve transformation.

The personnel who are now the senior technical staff of the ADAPT Service Corporation each have a decades experience with analysis in the eigenvector space. This has led to the development of aunique set of computer programs both to perform the transformation to the eigenvector space and to perform the analysis in this space.

The ADAPT programs have many outputs which are considerably different from those which are obtained from classical approaches to empirical or statistical analysis. This attachment will attempt to present a brief description of these outputs and how they may be used to improve empirical data analysis. In the following paragraphs, we will summarize each of the capabilities and cutputs of the ADAPT analysis procedure.

ADAPT OPTIMAL REPRESENTATION

The major difference between the ADAPT approach to empirical analysis and the classical approach to empirical analysis is the derivation and use of the ADAPT optimal representation to simplify and improve all subsequent empirical analysis of the data. The ADAPT optimal representation is known in the literature under the names of: 1) principal component analysis, 2) Karhunen-Loeve expansion, 3) eigenfunction expansion and 4) optimum empirical orthogonal functions. The ADAPT Service Corporation has developed a unique approach to obtaining this transformation which overcomes the difficulties associated with the iterative techniques discussed in the literature and available in most "statistical"packages". The importance of this unique approach to deriving eigenvectors is discussed in the ADAPT write-up titled "significance of ADAPT Approach to Deriving Eigenvectors" included as Appendix 2B.

It is useful to review some of the basic concepts associated with the ADAPT optimal representation. The first point which must be established is the meaning of optimal. For the ADAPT application, optimal is defined as that representation which requires the least number of numbers to represent a given amount of information or variation. Thus, by definition, the ADAPT optimal representation

is the most efficient orthogonal coordinate system for representing the learning data. For further discussion of this transformation and its use see References 1-3.

After the optimal representation has been obtained, the learning data is transformed to the optimal space and the analysis is performed in the optimal space. The optimal space may be viewed either geometrically as a new coordinate system for describing the learning data of functionally as a system of empirical orthogonal functions (EDF) to be used to construct a generalized Fourier series representation of the learning data. In the first case, the analysis is performed on the coefficients of each of the data vectors in the new space. In the latter case, the analysis is performed on the coefficients of the generalized Fourier series expansion of each of the data histories. The numerical value of the coefficients is identical regardless of whether the procedure is visualized geometrically or functionally. Thus, the major output of the first step of any ADAPT analysis is the transformation matrix to transform the data from the original data space in which the data vectors are defined to the new optimal ADAPT analysis space.

To visualize the role of the ADAPT representation, consider the transformation matrix H_n between the original data space containing observation or data vectors "SV_{kn}" and the optimal analysis space containing the transformed data vectors "Y_{kr}". Figure 1 presents a block diagram of the ADAPT process illustrating this role of the optimal space. The transformation matrix, H_n, is an orthogonal matrix, the inverse of this transformation is equal to its transpose. Thus, one has rules for transforming the data to the optimal space and the results of the analysis from the optimal space back to the original space. The dimensionality of the original space which using the notation of Figure 1 is K by n will be reduced to K by r where K is the number of cases and n is the number of dimensions or number of numbers required to describe each case. In general, for large data sets, r is at least an order of magnitude less than n. For data vectors less than the order of one hundred, r may only be a factor of 2 to 10 less than n. The data in the original data space is designated by the symbol V_{kn}. In the optimal space, his data is represented by the coefficients Y_{kr}. Where K in both cases designates the case and n and r designate the components of the data vector in each of the spaces, respectively. One may transform the

FIGURE -1 - BLOCK DIAGRAM OF ADAPT PROCESS

ORIGINAL DATA SPACE	ADAPT DERIVED TRANSFORMATION MATRIX	OPTIMUM SPACE
$\begin{matrix} SV_{11} & SV_{12} & SV_{13} \cdots & SV_{in} \\ SV_{21} & SV_{22} & & \\ \vdots & & & \\ SV_{k1} & \cdots & \cdots & SV_{kn} \end{matrix}$	H_{rn} $H^{-1} = H^{t}$	$\begin{matrix} Y_{11} & Y_{12} & \cdots & Y_{1nr} \\ Y_{21} & & & \\ \vdots & & & \\ Y_{k1} & \cdots & \cdots & Y_{knr} \end{matrix}$
DIMENSION: $K \times N$		$K \times NR$
DATA: $SV_{k,n}$	$Y_{k,r} = \sum_n SV_{kn} H_{nr}$ (1) $SV_{k,n} = \sum_n Y_{kr} H_{rn}$ (2) (Generalized Fourier)	$Y_{k,r}$
ALGORITHM: $W_k = \sum_n \bar{A}_n SV_{nk}$ (3)	$\bar{A}_n = \sum_r H_{nr} A_r$ (4)	$W_k = \sum_r A_r Y_{rk}$ (5)

THUS: r-th OPTIMAL FUNCTION = $H_{r,n}$

RELATIVE IMPORTANCE VECTOR = $\bar{A}_n$

AND: W_k = THE DETECTION STATISTIC OR ESTIMATE

RELATIVE IMPORTANCE SPECTRA = A_r

SCATTER PLOT Y_{1k} vs Y_{2k}

data either from the original data space to the optimal space or visa versa by using the transformation matrix as indicated by the arrows on Figure 1. Linear algorithms may also be transformed between the data space and the optimal space by use of the H matrix.

The ADAPT characteristics which in addition to the classical statistical summary parameters would be of interest include the ADAPT optimum function, the information energy plot, the ADAPT scatter plot, the ADAPT relative importance vector, performance map, independent eigenscreening and the empirical validity criteria. The following paragraphs will present a brief description of each of these and some of the ADAPT preprocessing concepts.

Optimum Function

Referring to the preceding descrption of the ADAPT process, the ADAPT optimum function is numerically the corresponding column of the H matrix. Since this vector is described by N components, it has the appearance of a data vector that shows the importance of each of the original components of the data vectors to the construction of the optimal space. Plots of this function provide a physical interpretation for the components of the optimal space and also an indication of which of the original data vector components are conveying similar information. This may be viewed as an analysis of variation of the data but it should not be confused with the classical analysis of variation which is normally associated with the outputs of regression analysis. These classical analyses of variation generally describe how much of the variation observed in the dependent variable can be explained by the independent variable. The ADAPT optimal functions on the other hand, are simply an analysis of variation of the independent variable without considering the dependent variable at all. It seeks to answer the question which independent variables express the greatest amount of variation and which independent variables convey similar information.

Information Energy Plot

The eigenvalues associated with each of the optimal

functions' defines the amount of variation in the learning data set which is explained by that optimal function. Since all information must be conveyed by variation in the data, this variation is analogous to an "information energy". One of the standard ADAPT outputs which will be provided for each of the bases developed (i.e. transformation matrices) in this study is a plot of this information energy or eigenvalue as a function of a number of dimensions used. Examination of this information energy curve allows one to determine the dimensionality at which the information has the character of noise. One can also observe the change of character of the information represented as a function of dimensionality. It is often possible to detect the point at which the eigenvectors are primarily correcting for anomolous cases! Thus, the information energy is one of several important tools in selecting the dimensionality for the analysis. Some of the subtle aspects associated with analysis of the information energy are discussed in references 4-6. Ref-4 is a fundamental paper, the results are often misused. Ref-6 discusses this in more detail.

Scatter Plot

The ADAPT scatter plot is the projection of the data vectors under consideration on two dimensions of the optimum space. In general, one projects on the first two dimensions on the optimal space since these two dimensions provide the best representation of the information contained in the data. This is identical to making a scatter plot of the Y_{1k} versus Y_{2k} coefficients. Note, that equation 2 on Figure 1 can be interpreted as the generalized Fourier series expansion of data history SV_k in terms of the orthogonal functions defined by the H matrix. Thus, a data history, SV_{pn} having a first coefficient of 1, ($Y_{1p} = 1$), on the scatter plot and a second coefficient of -1, ($Y_{2p} = -1$), would have a two term generalized Fourier series representation equal to the difference between the first and second optimal functions ($SV_p = H_1 - H_2 \quad \ldots$). The significant achievement of the scatter plot of the first two optimal coefficients of each of the data vectors is that it presents the best possible two dimensional representation of the entire data set. Each point on the scatter plot represents an entire history made up of N points.

Algorithm and Relative Importance Vectors

The derivation of a linear classification algorithm may be looked upon as the search for the line or vector with the property that the numerical value of a data vector's projection on this line is a good detection statistic. The ADAPT algorithm vector is a plot of the components of the projection of this vector in the original data space. Since the dot product of this vector with the data vector determines the detection statistic, the magnitude of each of these components provides a measure of the importance of each component to the algorithm being evaluated. In the ADAPT programs, the algorithm vector is derived in the optimal space. Thus in data space this vector is the product of the vector defined in the optimal space, A_r times the transformation matrix H_{nr}.

The importance of any variable to an algorithm is the product of two values: 1) the value of the algorithm associated with that value and 2) the amount of variation associated with the variable. For example, a given variable makes no contribution to an algorithm if the algorithm value is zero or if it has the same value for all observations. Thus, we define the relative importance vector as a vector in data space where each component is the product of the algorithm value and the variance of the variable associated with that component. It follows from the mechanism of the dot product operation that it is the absolute value of the relative importance (or algorithm) vector which is significant. For example, considering the algorithm vector, if one variable has a value of minus .5 and another variable a value of plus 0.1 a change in the indexing variable having the value of minus 0.5 in the algorithm vector has five times the effect on the answer or detection statistic as the same change in the indexing variable having a value of plus 0.1.

Performance Map

The performance map is a plot of the dimensionality used for the analysis versus the performance of the algorithm developed. It provides an empirical non-parametric tool to determine whether there was sufficient learning cases

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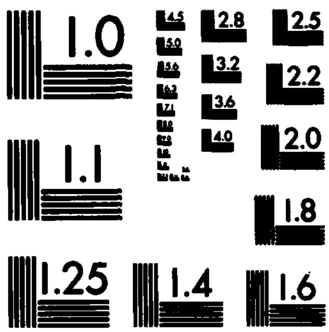

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

to provide a physically meaningful algorithm. It also provides a tool for estimating the gains possible by increasing the amount of training data. The task accomplished is analogous to the problem of fitting a third order polynomial to independent test data. One can always fit a third order polynominal to three numbers, and there is no implied physical significance to the fact that there is a good fit. This is often referred to as an overdetermined problem. On the other hand, if one has a "large" number of independent samples say one hundred samples and one fits a curve to this larger set of samples, one may conclude that those hundred samples can be approximated by a third order polynomial expression over the range of the available experimental data.

The question is, what is "large"? The same phenomena occurs for all empirical analysis. If the number of learning cases equals the number of dimensions, most empirical algorithms will fit the learning data exactly, however, once again there is no physics implied in this fit. As one increases the number of learning cases beyond this point, if one continues to achieve good fits of the data with the empirical algorithm, the probability that the fit is based on physics increases. Eventually when the ratio of learning cases to number of dimensions used is "sufficiently large", one not only can assume that the relationship is based on physics but that the performance which is obtained on the learning data may safely be extrapolated to future independent test samples. The ADAPT performance map can be used to define "sufficient large".

After introduction of the independent eigenscreening concept into the ADAPT linear classification and regression programs, the performance map was no longer required to determine if the overdetermined situation had been obtained. However, the performance maps are now easier to use and still determine if additional training data should be used. They now provide plots of both the biased and unbiased performance as a function of ratio of number cases to dimensionality. When both the biased and unbiased performances are similar, the number of training cases are adequate for that algorithm.

<u>Empirical Validity Criteria</u>

The ADAPT approach of preceding the empirical analysis with an optimal representation also provides a mechanism

for performing a necessary but not sufficient test to determine whether an empirical algorithm is applicable to a new independent test sample. This empirical validity criteria consists of obtaining the ratio, (Q) of the length of the data vector for the new independent test case in the optimal space to its length in the original data space. If this ratio is significantly less than the corresponding ratio for the average or typical learning data used to derive the algorithms, the independent test case has been obtained from a sample which is significantly different from the learning data. Thus, empirical analysis of the test case based on algorithms derived from that learning set can not be justified. Experience with this validity criteria in many different problems, has shown it to be very effective in providing apriori estimate of whether an algorithm is applicable to a particular test case. This procedure has been part of the ADAPT family of computer programs and was first described in the literature in Ref-7.

Group-Out Independent Testing

The ADAPT regression and classification algorithm development programs include a capability to obtain independent (i.e. unbiased) test results with a minimum increase in the required number of cases. This is achieved through the group-out testing procedure. The procedure is to consider the original training set of data as made up of a relatively large number of small groups of cases. Note, that the group may be as small as one case. If we have a set of M cases available for the study and we use groups of N cases each, the procedure is to remove the first group of N cases giving a training set of M minus N cases and an independent test set of N cases. The algorithms are derived on the training set and tested against the N cases in the first group. When this is completed, the N cases in the first group are returned to the training set and a second group of N cases is removed and the procedure repeated. If this procedure is followed, one finds that they have derived a total of M divided by N algorithms each having M minus N training cases and has tested the total of all of these algorithms against M independent test cases. Thus, the net effect of this procedure is to effectively provide M minus N training cases and M independent test cases from a set of M cases.

It should be noted, that the procedure originally reported in the literature in Ref-8 is based on the capability to obtain an inverse with one case omitted from the covariance matrix. In the ADAPT programs, our ability to use this procedure is due to the efficiency of the analysis in the ADAPT space. Although we also have some programs which make use of the procedure outlined in the literature combined with the efficiency of the ADAPT analysis space which provides an extremely economical way of performing one-out testing. We have compared the performance obtained with the group-out testing with classical independent testing and have found with random selection of groups, stable sets of algorithms produce identical results as independent tests when training and test samples are drawn from homogeneous data. With conservative selection of groups the group-out testing is a more severe test.

Eigenscreening

Classical screening regression has been avoided in the development of the ADAPT computer programs for two reasons. These reasons are: 1) classical screening regression makes the screening decision based on the performance established from training data. Comparative analyses between use of independent test data and training data performed by the ADAPT Service Corporation have shown that the training data does not provide a reasonable basis for screening of the variables and 2) classical screening is performed on a set of independent variables which are not orthogonal and thus considerable effort is required ascertain whether a variable is retained because it is significant or because it is repeating information which has already been obtained in a different variable.

The ADAPT eigenscreening approach is similar to the classical screening regression except that the screening is performed in eigenvector space and performance is established based on the group-out testing procedure and thus is based on independent and unbiased test results. Since the screening is performed in the eigenvector space instead of the data space, the variables being screened are orthogonal and one need not be concerned with the linear dependence between the screened variables.

The screening process is significantly improved because: 1) the unbiased test provides a higher confidence performance estimate than dependent testing and 2) the group-out testing allows the evaluation of the stability of each term in the algorithm as well as the algorithm performance. The evaluation of the stability is especially important when the number of cases is limited, since the "overdetermined" solution, which must be avoided, is very unstable. If the performance of the different algorithms developed in the group-out testing is unstable, one can be certain that there are insufficient training cases. If any term in the algorithm is unstable, this term probably should have been rejected.

These improvements in the screening have resulted in significant additional capabilities in performing regression analysis. The ADAPT Service Corporation has also applied these procedures to pattern recognition techniques and has computer programs which provide these same advantages to the development of classification algorithms. Further discussion and examples illustrating the ADAPT eigenscreening are given in the ADAPT write-up "Illustration of ADAPT Independent Eigenscreening Technique", included as Appendix C3D.

Preprocessing

An extremely important factor in obtaining good empirical results is to preprocess the data such that the information is presented in a useful manner. The ADAPT family of computer programs include the capability to provide most of the classical preprocessing, such as normalizations, adjusting the data according to some prescribed function, taking Fourier or cepstrum transforms of the data. The ADAPT computer programs also include specialized preprocessing which has been developed based on requirements established as a result of the work performed in the past. These include such techniques as equalization, thresholding and a unique capability for objectively deriving folding procedures to overcome non-linearities and non-monotonic relations between the predictant and the predictor variable.

The last preprocessing performed before processing the data through the ADAPT eigenvector derivation programs or transforming the data to the eigenspace is to reduce the data to zero mean by subtracting the average of all the training cases from each data vector. The zero mean data offers a great many numerical advantages and is used in almost all ADAPT studies.

In all studies where different types of variables (eg. a data vector composed of temperature measurements and pressure measurements) and many cases where the variables are the same but their magnitudes may mask the variation, the reduction to zero mean is preceded by "<u>equalization</u>" of the data vector. This is a process by which the value of each variable is forced to lie between 1.0 and 2.0. This is accomplished by transforming the original variable $V_k(x)$ to a new variable $\widetilde{V}_k(x)$ using:

$$\widetilde{V}_k(x) = 1 + \frac{V_k(x) - VMIN(x)}{VMAX(x) - VMIN(x)} \qquad (1)$$

where $V_k(x)$ = Value of observation k associated with index x

X = A range of one or more indexing variables

VMAX = Max value over all training data associated with index x

VMIN = Min value over all training data associated with index x

APPENDIX B - SIGNIFICANCE OF ADAPT APPROACH TO DERIVING EIGENVECTORS

INTRODUCTION

The ADAPT approach to empirical data analysis is that empirical data analysis such as pattern recognition or regression should be preceded by transforming all of the data into the appropriate eigenvector space for analysis. This provides an optimum (in the Karhunen-Loeve sense) space in which to perform the analysis and significantly decreases the cost and increases what can be learned from any subsequent analysis. This approach translates most of the major numerical analysis problems into the first step (i.e. finding the eigenvectors of the covariance matrix derived from the original data vectors). Thus, the efficient and correct derivation of the eigenvectors associated with a covariance matrix is one of the most important aspects of the ADAPT approach to empirical analysis.

The ADAPT Service Corporation uses a unique approach to the derivation of these eigenvectors which provides both a greater efficiency with respect to computer running time and core size and also eliminates the problems resulting from noisy and/or ill-conditioned real data sets. These noise and data conditioning problems are very similar to the problems which lead to singular matrices when analyzing data in the original data space. Although these problems do not cause a failure to obtain an answer with conventional eigenvector techniques such as those included in the IBM scientific sub-routine package they often lead to meaningless outputs from these techniques and unnecessarily large requirements for core size and running time. This appendix will review these difficulties and outline the advantages of circumventing these difficulties prior to entering the procedures for deriving eigenvalues and eigenvectors.

PITFALLS OF CONVENTIONAL EIGENVECTOR DERIVATIONS

Since we are dealing with the task of finding the eigenvectors of the covariance matrix, we may limit the discussion to real symmetric matrices. Modern techniques (i.e. the Jacobi technique which is used in the IBM scientific sub-routine package or the Givens-House-holder technique described in Reference 1 and used in many commercially available statistical packages are based

on iterative techniques which usually proceed from some initial guess for the eigenvalues and an apriori specified accuracy. With the judicial use of overflow and underflow protections in the programming of these techniques, one obtains a set of numbers and vectors which look like eigenvalues and eigenvectors. In many ways, this is unfortunate because unlike the situation with matrix inversion where ill-conditioned input data leads to the impossibility of obtaining an answer, ill-conditioned data leads to a partially incorrect answer with these eigenvector techniques. These incorrect outputs are responsible for many of the misconceptions concerning eigenvector analysis that are often heard and occasionally even appear in the literature regarding the use of eigenvectors as an analysis tool. The most common of these misconceptions are:

1) the instability of eigenvectors (i.e. cases where eigenvectors corresponding to relatively large eigenvalues are supposedly unstable as one changes the data slightly),

2) the statement that the derivation of eigenvectors for large real data vectors is nearly computionally impossible (zb: Reference 2, Page 31) and,

3) only the first few dominant eigenvectors can have physical meaning (the ADAPT Service Corporation has found and verified physically meaningful information in eigenvectors explaining considerably less than 1% of the variation).

In the following paragraphs, we will discuss two problems which may lead to such false conclusions, these are:

1) insufficient independent observations and,

2) noise.

The inpact of insufficient observations can be seen most clearly by considering a simple case. Suppose for example one had three observations (i.e. cases) of some phenomena where each observation consisted of five independent measurements associated with the phenomena being observed. This will provide a data matrix consisting of three vectors of five components each. Clearly, if one attempted to run a five dimensional regression or a discriminate analysis requiring the inversion of the covariance matrix in this five dimensional original data space, they would not be surprised to find that the matrix to be inverted is singular. Similarly, one should

not expect to be able to find five eigenvectors associated with this data set. Table 1 shows an example using the Givens-Householder technique where the substitution of the covariance matrix associated with these three five component data vectors into conventional eigenvector routines will lead to five eigenvalues and five associated eigenvectors. The two smallest eigenvalues and their associated eigenvectors must be meaningless and should be discarded.

TABLE 1 - SAMPLE VECTORS AND EIGENVECTORS DERIVED USING GIVENS-HOUSEHOLDER TECHNIQUE

3 - INPUT VECTORS

V1 =	-10.	0.	0.	0.	0.2
V2 =	0.	1.	0.	0.	0.
V3 =	10.	-1.	0.	0.	-0.2

5 - EIGENVECTORS AND CORRESPONDING EIGENVALUES:

	EIGENVECTORS					EIGENVALUE
E1 =	0.9985	-0.0503	-0.0200	-4.3E-12	0.0	200.
E2 =	0.0503	-0.9987	5.6E-8	-2.2E-17	-5.7E-17	1.5
E3 =	-2.8E-20	-7.0E-17	2.2E-10	-1.0	-1.0	6.0E-18
E4 =	0.	0.	0.	0.	1.0E-11	2.8E-16
E5 =	-0.0200	-0.0010	-0.9998	-2.2E-10	1.4E-15	0.0

If we now introduce two additional cases which are linearly dependent on the original three cases, there will be no charge in the above described situation except that in general the eigenvalues and the eigenvectors will change. However, if these two linearly dependent eigenvectors are noisy they may introduce additional positive eigenvalues, making the uses believe that there are more than three meaningful eigenvectors, even though a maximum of three eigenvectors can have any meaning. We would hope that these eigenvectors were those associated with the largest eigenvalues, however, this can not be assured. If each of the data vectors were similar such that the first eigenvector explained almost all of the variation and the second and third eigenvectors only explained a small amount of the variation, the eigenvalues of the noise generated eigenvectors may exceed the eigenvalues of the true eigenvectors. Thus, the ill-conditioned data which leads to most problems appearing as singular matrices in data space analysis when combined with noisy data will lead to the generation of false eigenvectors when one attempts to derive eigenvectors with most modern iterative techniques. Thus, the data conditioning necessary to insre successful results in the data space analysis is equally important to deriving the eigenvectors.

When dealing with real data especially with real data defined by a large number of observations especially where the number of cases is only slightly greater than the number of measurements defining each of the observations, linear dependence of cases within this data and noise may create these problems even where one would not expect them. Noisy data further aggravates the problem by decreasing the number of independent observations. Large sets of real data where each data vector is itself a high dimensional vector are particularly susceptable to a noise induced linear dependence. That is, although a given observation may in principal be independent of all other observations it may be sufficiently similar that the difference between it and another observation is within the noise or the inaccuracies of the measurements. When this occurs, it can dramatically decrease the number of independent cases available and it is often difficult to determine this effect apriori by examination of the data or even the physics of the process. Since this noise induced linear dependence will also reduce the total number of eigenvectors which can be expected from the covariance matrix, it's effect can appear in exactly the same way as the simple example given

above. Thus, we see that in dealing with real data, the use of poorly conditioned data in conventional eigenvector derivation procedures can lead to a large percentage of the eigenvectors being generated from measurement inaccuracies or other noise and having no real relationship to the data. Furthermore, this has been accomplished with a great deal of unnecessary effort on the part of the computer. This unnecessary effort has increased both the core size and running time required.

ADAPT EIGENVECTOR TECHNIQUE

The ADAPT technique to circumventing the conventional problems in deriving eigenvector representations is to precondition the data matrix by a proprietary procedure which eliminates the above described problems and is mathematically equivalent to orthogonalizing the matrix without optimizing. This preconditioned data is then used to derive the Karhunen-Loeve expansion appropriate to the original data.

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APPENDIX-C

ILLUSTRATION OF ADAPT INDEPENDENT EIGENSCREENING TECHNIQUE

Tables 1 through 3 present typical outputs from the ADAPT independent eigenscreening programs. These tables illustrate the development of a regression algorithm using independent eigenscreening for estimating the change in longitude of a tropical storm 24 hours after its observation. Before using these tables to illustrate the independent eigenscreening technique, we will describe the information presented on the tables. The tables consist of ten columns, each of these columns defines one parameter of interest.

To understand the information presented, we must recall that the procedure used is to divide the training cases into two groups, the first group to be used as training and the second group as independent test. For example, consider a set of 60 training cases, we might take the first 50 as the training and the last 10 as independent test. The algorithms would then be derived using the first 50 cases and tested against the last 10. When this is completed, a different set of 50 training cases and 10 independent would be used. For example, we might now take Cases 1 through 40 and 51 through 60 as training data and test the results against Cases 41 through 50. After completion of the second set of algorithms and independent tests, we could repeat the procedure four more times. This would yield six different training algorithms and sets of 10- independent tests on each of the six algorithms for a total of 60 independent test cases. Thus, beginning with a total set of 60 cases this procedure would result in 50 cases for training and 60 independent test cases.

The selection of six sets of algorithms and the composition of each set are input parameters and are selected based on the physics of the problem. The penalty is that we need to develop six sets of algorithms. Using conventional techniques the cost of this procedure would be prohibitive for most real problems, but with the ADAPT procedures we can take this approach. As a result of this approach, we have a performance for the independent test cases, in this case, the correlation coefficient given in the third column of the tables and labeled RHOZVT. We also have a learning correlation coefficient for each of the six algorithms developed. The average of these

coefficients is given in the fourth column of the table and labeled RHOVL. We may also compute the standard deviation of this learning correlation coefficient and if the algorithm is stable we would expect that the standard deviation of the learning correlation coefficients would be small compared to the average learning correlation coefficient. Thus, we define the ratio of the standard deviation to the average correlation coeffient of the learning data as the learning stability. This is provided in the tenth or last column of the table under the title, "Learn Stab".

Since we have developed six algorithms and each algorithm has a number of terms in it equal to the dimensionality of the analysis given by Column 2 in the tables, we can also examine the stability of each term in the algorithm in the same way as we examine the stability of the performance. This stability is given in the tenth column of the table under the title of MAXSIG/MEAN. The value given is the value of the worst stability of any term in the algorithm, the number, NO, is given for some outputs and is the term in the algorithm which has this worst stability. When the stability exceeds an input threshold parameter, the entire stability for the algorithm is printed out (on a separate page from this summary table) so that the user may examine it. Our experience has shown that the learning stability is an almost certain test of having obtained the overdetermined solution. Experience with a number of different types of data and problems suggests that the stability parameter, MAXSIG/MEAN must be less than 0.4 to 0.5 for all terms. The most complete test of this is reported in Section 2.4, performance evaluation methodology of the body of this report.

The fifth column in the tables labeled, ACT-EST, gives the average error based on the independent testing. The three columns labeled, SDZV, SIGRATL, or SIGRZVDT, list the standard deviations and ratios of standard deviations which we have found useful in assisting in the understanding of the performance of the algorithms which have been developed.

The first column of Table 1 showing the potentially useful eigendirections provides a definition of which eigendirections are being used in any algorithms developed. In order to provide brevity in the table, only the last eigendirection added is listed. Thus, the bottom row of the first column of this table has a value: "2", this indicates that the first eigendirection which was useful was the second eigendirection and that the algorithms developed to determine this

were developed in the one dimensional space (i.e. Column 2 headed NR has a value of NR = 1) consisting of the second eigendirection. The second row up shows that Column 1 contains the value "4". This indicates that the fourth eigendirection was the second useful eigendirection and the algorithm to

determine this was derived in the two dimensional eigenvector space consisting of the second and fourth eigenvectors. Thus, if one were to read at the tenth row up from the bottom this is an algorithm developed in a ten dimensional space consisting of all of the eigendirections shown in the first column from the tenth row down to the first row.

Now that we have looked at the format of Tables 1 through 3, we shall discuss their meaning. Table 1 summarizes all of the eigendirections which have been selected for retention based on the input parameters given by the user. That is, the user is allowed to input a criteria for both the independent test results and the stability which must be satisfied in order to retain a given eigendirection as a result of this screening. Table 2 shows the same results for those eigendirections which have been rejected based upon these criteria. In general, it is our practice on the first screening run to put in very weak constraints on the retention of eigendirections so that we retain any eigendirection which has any possibility of being useful in the analysis in this first pass. For this study, this yielded a total of 19 eigendirections which appeared to have some usefulness for the task at hand. We then repeat the screening procedure in reverse. That is, we start with all of the potentially useful eigendirections and sequentially delete one of the eigendirections and determine whether its deletion has improved or decreased the performance of the algorithm. It sometimes requires several steps and Table 3 presents the results of the last step of this analysis. This table has the same format as Tables 1 and 2. In general, the criteria utilized are somewhat more stringent in these final steps. Examination of this table immediately shows the most successful algorithm, is the ten dimensional algorithm using eigendirections 53, 42, 34, 31, 20, 11, 8, 7, 6 and 4. Note, that at dimensionalities greater than or equal to eleven both the error and the stability

of the termsin the algorithm (MAX SIG/MEAN) deteriorate. This table then completes the screening process.

In summary, because of the efficiency of the ADAPT process, we have been allowed to make our decisions as to the value of retaining eigendirections based on independent tests as well as on the stability of the terms in the algorithm and the performance of the algorithm. Furthermore, we have not had to concern ourselves with the possibility that a given direction is being retained because of linear dependence on another eigendirection because of the orthogonal properties of the eigendirections. Although this example has been given for a regression analysis, our programs are completely operational and provide exactly the same results using similar outputs for a Fisher classifier. Similar procedures can be prepared for any linear classifier.

TABLE-1

SUMMARY OF STORM OUT TESTING RUN ON 12 NOV 1979 (NR'S KEPT)

ATLANTIC-E-PAC PARTITION UNBIASED 288CASE BASE THIS SET=103 CASE (64)
*** CHG LONG *** AT 24HRS AFTER OBSERVATION-

LAST ACT-AVGL = 0.1698E 03

LAST STDDEV ACT = 0.2047E 03

?IG NR	NR	RHOZVT	RHOVL	ACT-EST	SDZV	SIGRATL	SIGRZVBT	MAX NO.	SIG/MEAN VALUE	LEARN STAB
59	19	0.7674E 00	0.8521E 00	0.1051E 03	0.1344E 03	0.5225E 00	0.6411E 00	14	0.526E 00	0.5129E-01
54	18	0.7550E 00	0.8459E 00	0.1072E 03	0.1348E 03	0.5320E 00	0.6430E 00	8	0.484E 00	0.5941E-01
53	17	0.7553E 00	0.8345E 00	0.1065E 03	0.1374E 03	0.5495E 00	0.6554E 00	8	0.722E 00	0.6166E-01
45	16	0.7559E 00	0.8289E 00	0.1081E 03	0.1373E 03	0.5581E 00	0.6547E 00	8	0.557E 00	0.5715E-01
42	15	0.7532E 00	0.8251E 00	0.1069E 03	0.1379E 03	0.5636E 00	0.6578E 00	8	0.825E 00	0.5683E-01
39	14	0.7473E 00	0.8220E 00	0.1056E 03	0.1363E 03	0.5681E 00	0.6645E 00	8	0.429E 00	0.5533E-01
35	13	0.7477E 00	0.8192E 00	0.1097E 03	0.1393E 03	0.5724E 00	0.6645E 00	8	0.506E 00	0.5189E-01
34	12	0.7409E 00	0.8151E 00	0.1101E 03	0.1384E 03	0.5764E 00	0.5626E 00	8	0.406E 00	0.4737E-01
31	11	0.7323E 00	0.7951E 00	0.1140E 03	0.1441E 03	0.6059E 00	0.6777E 00	8	0.368E 00	0.3309E-01
21	10	0.7240E 00	0.7895E 00	0.1159E 03	0.1446E 03	0.6131E 00	0.6899E 00	7	0.377E 00	0.3518E-01
20	9	0.7210E 00	0.7808E 00	0.1161E 03	0.1453E 03	0.6242E 00	0.6929E 00	6	0.571E 00	0.3090E-01
15	8	0.7205E 00	0.7723E 00	0.1172E 03	0.1454E 03	0.6347E 00	0.6935E 00	6	0.423E 00	0.3037E-01
14	7	0.7216E 00	0.7699E 00	0.1178E 03	0.1452E 03	0.6377E 00	0.6924E 00	7	0.347E 00	0.2900E-01
12	6	0.7236E 00	0.7639E 00	0.1179E 03	0.1447E 03	0.6449E 00	0.6902E 00	6	0.209E 00	0.2743E-01
11	5	0.7221E 00	0.7607E 00	0.1134E 03	0.1451E 03	0.6483E 00	0.5918E 00	4	0.179E 00	0.2703E-01
8	4	0.6615E 00	0.7186E 00	0.1300E 03	0.1573E 03	0.6950E 00	0.7500E 00	4	0.193E 00	0.2423E-01
7	3	0.6497E 00	0.7089E 00	0.1334E 03	0.1594E 03	0.7051E 00	0.7602E 00	1	0.147E 00	0.2003E-01
6	2	0.5548E 00	0.6088E 00	0.1436E 03	0.1744E 03	0.7931E 00	0.8320E 00	1	0.151E 00	0.1614E-01
4	1	0.4716E 00	0.4859E 00	0.1446E 03	0.1849E 03	0.8729E 00	0.8818E 00	1	0.708E-01	0.2556E-01

TABLE - 2

SUMMARY OF STORM OUT TESTING RUN ON 12 NOV 1979 (NR'S DROPT)

ATLANTIC-E-PAC PARTITION UNBIASED 288CASE BASE THIS SET=103 CASE (64)
*** CHG LONG *** AT, 24HRS AFTER OBSERVATION-

LAST ACT-AVGL = 0.1698E 03

LAST STDDEV ACT = 0.2097E 02

S NR	NR	RHOZVT	RHOVL	ACT-EST	SDZV	SIGRATL	SIGRZVBT	MAX SIG/MEAN	LEARN STAB
60	20	0.7494E 00	0.6530E 00	0.1096E 03	0.1386E 03	0.5209E 00	0.6621E 00	0.1306E 01	0.5385E-01
58	19	0.7582E 00	0.8473E 00	0.1086E 03	0.1367E 03	0.5299E 00	0.6621E 00	0.8091E 00	0.5098E-01
57	19	0.7619E 00	0.8477E 00	0.1080E 03	0.1358E 03	0.5300E 00	0.6477E 00	0.7928E 00	0.5567E-01
56	19	0.7513E 00	0.8464E 00	0.1088E 03	0.1359E 03	0.5313E 00	0.6484E 00	0.2232E 01	0.5799E-01
55	19	0.7447E 00	0.8504E 00	0.1127E 03	0.1399E 03	0.5250E 00	0.6574E 00	0.8349E 00	0.5448E-01
52	17	0.7531E 00	0.8294E 00	0.1090E 03	0.1368E 03	0.5573E 00	0.6591E 00	0.1317E 01	0.578[illegible]E-01
51	17	0.7455E 00	0.8295E 00	0.1095E 03	0.1398E 03	0.5572E 00	0.6665E 00	0.4425E 01	0.570[illegible]E-01
50	17	0.7574E 00	0.8291E 00	0.1055E 03	0.1379E 03	0.5579E 00	0.6576E 00	0.2451E 01	0.5735E-01
49	17	0.7522E 00	0.8295E 00	0.1085E 03	0.1382E 03	0.5571E 00	0.6559E 00	0.6917E 00	0.5837E-01
48	17	0.7514E 00	0.8296E 00	0.1109E 03	0.1334E 03	0.5570E 00	0.6599E 00	0.6524E 00	0.5698E-01
47	17	0.7514E 00	0.8298E 00	0.1086E 03	0.1364E 03	0.5568E 00	0.6599E 00	0.7571E 00	0.5622E-01
45	16	0.7526E 00	0.8260E 00	0.1072E 03	0.1361E 03	0.5623E 00	0.6585E 00	0.7182E 00	0.5677E-01
44	16	0.7480E 00	0.8257E 00	0.1085E 03	0.1342E 03	0.5627E 00	0.6537E 00	0.1050E 01	0.5751E-01
43	16	0.7452E 00	0.8256E 00	0.1079E 03	0.1391E 03	0.5630E 00	0.6635E 00	0.1492E 01	0.5672E-01
41	15	0.7374E 00	0.8226E 00	0.1107E 03	0.1416E 03	0.5674E 00	0.6755E 00	0.4271E 01	0.5516E-01
40	15	0.7428E 00	0.8296E 00	0.1110E 03	0.1404E 03	0.5575E 00	0.6695E 00	0.4930E 00	0.4330E-01
37	13	0.7387E 00	0.8174E 00	0.1120E 03	0.1413E 03	0.5751E 00	0.6740E 00	0.7101E 00	0.4821E-01
36	13	0.7385E 00	0.8165E 00	0.1130E 03	0.1414E 03	0.5758E 00	0.6743E 00	0.9129E 00	0.4921E-01
35	13	0.7236E 00	0.8169E 00	0.1135E 03	0.1447E 03	0.5759E 00	0.6902E 00	0.1632E 02	0.4741E-01
33	12	0.7217E 00	0.7961E 00	0.1167E 03	0.1451E 03	0.6047E 00	0.6922E 00	0.5036E 01	0.3389E-01
32	12	0.7256E 00	0.7958E 00	0.1156E 03	0.1441E 03	0.6050E 00	0.6871E 00	0.2073E 01	0.3370E-01
30	11	0.7029E 00	0.7914E 00	0.1200E 03	0.1491E 03	0.6105E 00	0.7113E 00	0.2690E 01	0.3620E-01
29	11	0.7023E 00	0.7906E 00	0.1187E 03	0.1460E 03	0.6117E 00	0.7059E 00	0.1564E 02	0.3593E-01
28	11	0.7033E 00	0.7911E 00	0.1203E 03	0.1491E 03	0.6111E 00	0.7109E 00	0.4193E 01	0.3269E-01
27	11	0.7168E 00	0.7901E 00	0.1173E 03	0.1462E 03	0.6124E 00	0.6973E 00	0.2977E 01	0.3432E-01
26	11	0.7212E 00	0.7951E 00	0.1180E 03	0.1453E 03	0.6060E 00	0.6928E 00	0.4013E 00	0.3330E-01
25	11	0.7133E 00	0.7909E 00	0.1177E 03	0.1470E 03	0.6113E 00	0.7009E 00	0.1534E 01	0.3585E-01
24	11	0.6844E 00	0.7938E 00	0.1224E 03	0.1529E 03	0.6073E 00	0.7291E 00	0.9195E 00	0.4153E-01
23	11	0.7187E 00	0.7900E 00	0.1170E 03	0.1455E 03	0.6125E 00	0.6953E 00	0.6171E 01	0.3521E-01
22	11	0.7181E 00	0.7909E 00	0.1177E 03	0.1459E 03	0.6113E 00	0.6959E 00	0.9022E 00	0.3595E-01
19	9	0.7135E 00	0.7759E 00	0.1191E 03	0.1469E 03	0.6304E 00	0.7007E 00	0.5050E 00	0.2837E-01
18	9	0.7039E 00	0.7734E 00	0.1203E 03	0.1429E 03	0.6334E 00	0.7103E 00	0.6415E 01	0.2926E-01
17	9	0.7118E 00	0.7746E 00	0.1193E 03	0.1473E 03	0.6320E 00	0.7024E 00	0.5209E 00	0.3013E-01
16	9	0.7031E 00	0.7601E 00	0.1176E 03	0.1491E 03	0.6251E 00	0.7111E 00	0.7275E 00	0.3396E-01
13	7	0.7204E 00	0.7664E 00	0.1196E 03	0.1454E 03	0.6420E 00	0.6936E 00	0.4142E 00	0.2610E-01
10	5	0.6570E 00	0.7285E 00	0.1313E 03	0.1561E 03	0.6846E 00	0.7539E 00	0.3750E 00	0.2831E-01
9	5	0.6464E 00	0.7219E 00	0.1338E 03	0.1600E 03	0.6918E 00	0.7630E 00	0.9765E 00	0.1953E-01
5	2	0.4510E 00	0.4926E 00	0.1450E 03	0.1871E 03	0.8691E 00	0.8975E 00	0.7457E 00	0.2522E-01
3	1	0.0	0.1322E 00	0.1818E 03	0.2195E 03	0.9870E 00	0.1047E 01	0.8087E 00	0.1743E-01
2	1	0.0	0.1945E 00	0.1718E 03	0.2109E 03	0.9731E 00	0.1006E 01	0.3489E 00	0.1459E-01
1	1	0.0	0.1469E 00	0.1879E 03	0.2273E 03	0.9480E 00	0.1084E 01	0.1707E 01	0.7111E-02

THIS IS THE FIRST ENTRY TO THE 18AUG77 VERSION OF PSCAT

THIS SUBROUTINE MAKES A PRINTER SCATTER PLOT FROM THE TWO ARRAYS INPUT
IF OPLONG = .TRUE. THEN THE PLOT IS MADE SMALL ENOUGH TO FIT ON AN 8 X 11 SHEET OF PAPER
IF CRICAL = .TRUE. THEN THE SCALES ARE INPUT MANUALLY IN ABMAX, ABMIN, ORDMAX AND ORDMIN
CHAR CONTAINS A LIST OF THE SYMBOLS TO BE USED
[illegible] SPECIFIES HOW MANY TIMES EACH SYMBOL IS TO BE USED

TABLE - 3

SUMMARY OF STORM OUT TESTING RUN ON 13 NOV 1979

ATLANTIC-E-PAC PARTITION UNBIASED 288CASE BASE THIS SET=103 CASE (64)
*** CHG LONG *** AT 24HRS AFTER OBSERVATION-

LAST ACT-AVGL = 0.1698E 03

LAST STDDEV ACT = 0.2097E 03

ITG NR	NR	RHCZVT	RHOVL	ACT-EST	SDZV	SIGRATL	SIGRZVBT	MAX NO.	SIG/MIAN VALUE	LEARN STAB
38	14	0.7579E 00	0.8284E 00	0.1111E 03	0.1368E 03	0.5593E 00	0.6523E 00	6	0.467E 00	0.4665E-01
14	13	0.7606E 00	0.8249E 00	0.1098E 03	0.1361E 03	0.5644E 00	0.6492E 00	6	0.353E 00	0.4451E-01
12	12	0.7562E 00	0.8153E 00	0.1073E 03	0.1372E 03	0.5782E 00	0.6544E 00	12	0.429E 00	0.4433E-01
54	11	0.7575E 00	0.8138E 00	0.1057E 03	0.1369E 03	0.5803E 00	0.6528E 00	11	0.454E 00	0.4498E-01
53	10	0.7579E 00	0.8076E 00	0.1056E 03	0.1369E 03	0.5888E 00	0.6524E 00	6	0.262E 00	0.4575E-01
42	9	0.7525E 00	0.8010E 00	0.1097E 03	0.1381E 03	0.5977E 00	0.6584E 00	6	0.264E 00	0.4487E-01
34	8	0.7346E 00	0.7929E 00	0.1138E 03	0.1423E 03	0.6085E 00	0.6785E 00	6	0.333E 00	0.4026E-01
31	7	0.7239E 00	0.7742E 00	0.1156E 03	0.1447E 03	0.6326E 00	0.6899E 00	6	0.320E 00	0.2655E-01
20	6	0.7210E 00	0.7691E 00	0.1169E 03	0.1453E 03	0.6388E 00	0.6929E 00	6	0.343E 00	0.2634E-01
11	5	0.7221E 00	0.7607E 00	0.1184E 03	0.1451E 03	0.6485E 00	0.6918E 00	4	0.179E 00	0.2703E-01
8	4	0.6615E 00	0.7186E 00	0.1300E 03	0.1573E 03	0.6950E 00	0.7500E 00	4	0.193E 00	0.2423E-01
7	3	0.6497E 00	0.7089E 00	0.1334E 03	0.1544E 03	0.7051E 00	0.7602E 00	1	0.147E 00	0.2003E-01
6	2	0.5548E 00	0.6088E 00	0.1436E 03	0.1744E 03	0.7931E 00	0.8320E 00	1	0.151E 00	0.1614E-01
4	1	0.4716E 00	0.4859E 00	0.1446E 03	0.1849E 03	0.8729E 00	0.8818E 00	1	0.708E-01	0.2556E-01

APPENDIX D - CHARACTERISTICS OF ENGINE HEALTH EIGENVECTORS

The purpose of this appendix is to document the significant features of the eigenvector expansion which were not documented in the main body of the report. Two other appendices, A and B, provide the definition of the significance of the plots included in this appendix. The average vector used to reduce the data to zero mean, the information energy plot and the projection on the first two eigendirections were presented in the body of the report as Figures 11, 12 and 13, respectively of the body of this report.

Figures D1, D2 and D3 continue the projections on the next six eigendirections. They are plotted in the same format and using the same symbols as Figure 13.

Figures D4-D7 present plots of the data space representation of typical eigenvectors. Figures D4 show the dominant and intermediate eigenvectors. The dominant eigenvector is the first eigenvector. The largest contributes to this eigenvector is the engine test cell data. Eigenvectors 2-27 may be considered intermediate order eigenvector and have the characteristic that NOAP and test cell data are of similar importance. The 28th eigenvector and those shown in Figure D-6 may be called higher order eigenvectors and are dominated by the NOAP data with very little contribution from the test cell.

Referring to Figure 12 and the analysis given by Overland* suggests that possibly only the first eigendirection is physically unique. However, even the non-unique eigendirections are suitable as features in studies such as this. Furthermore, since any new intermediate or higher order eigendirection must be constructable by using a linear combination of the "near" eigenvectors, the general features of the intermediate and higher order eigenvector sets also remain unique.

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* Overland, James E.; "A Significance Test", Mon Wea Review, Vol 110, No-1.

FIG-D1 PROJECTION ON THIRD AND FOURTH ENGINE HEALTH EIGENDIRECTION

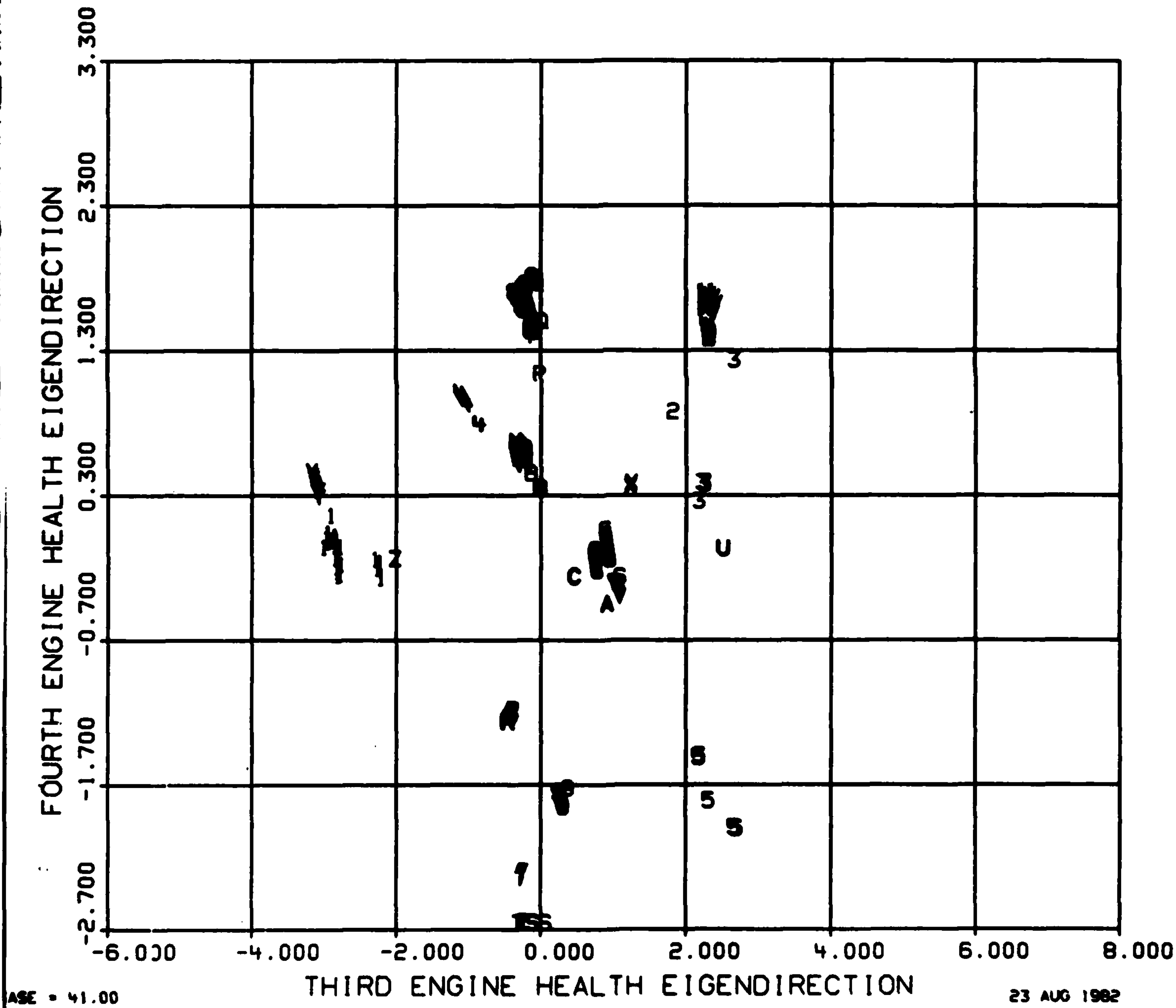


FIG-D2 PROJECTION ON FIFTH AND SIXTH ENGINE HEALTH EIGENDIRECTION

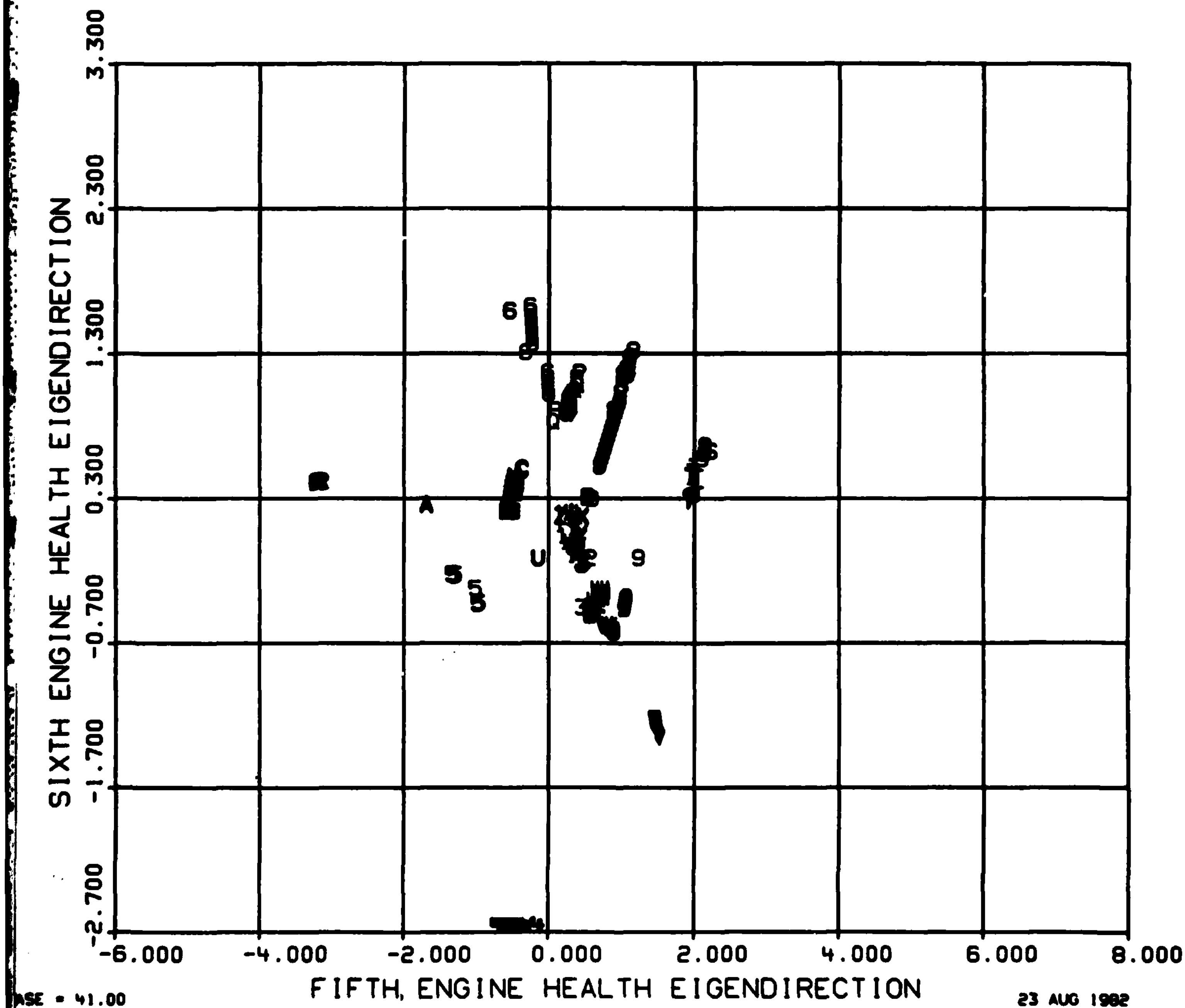
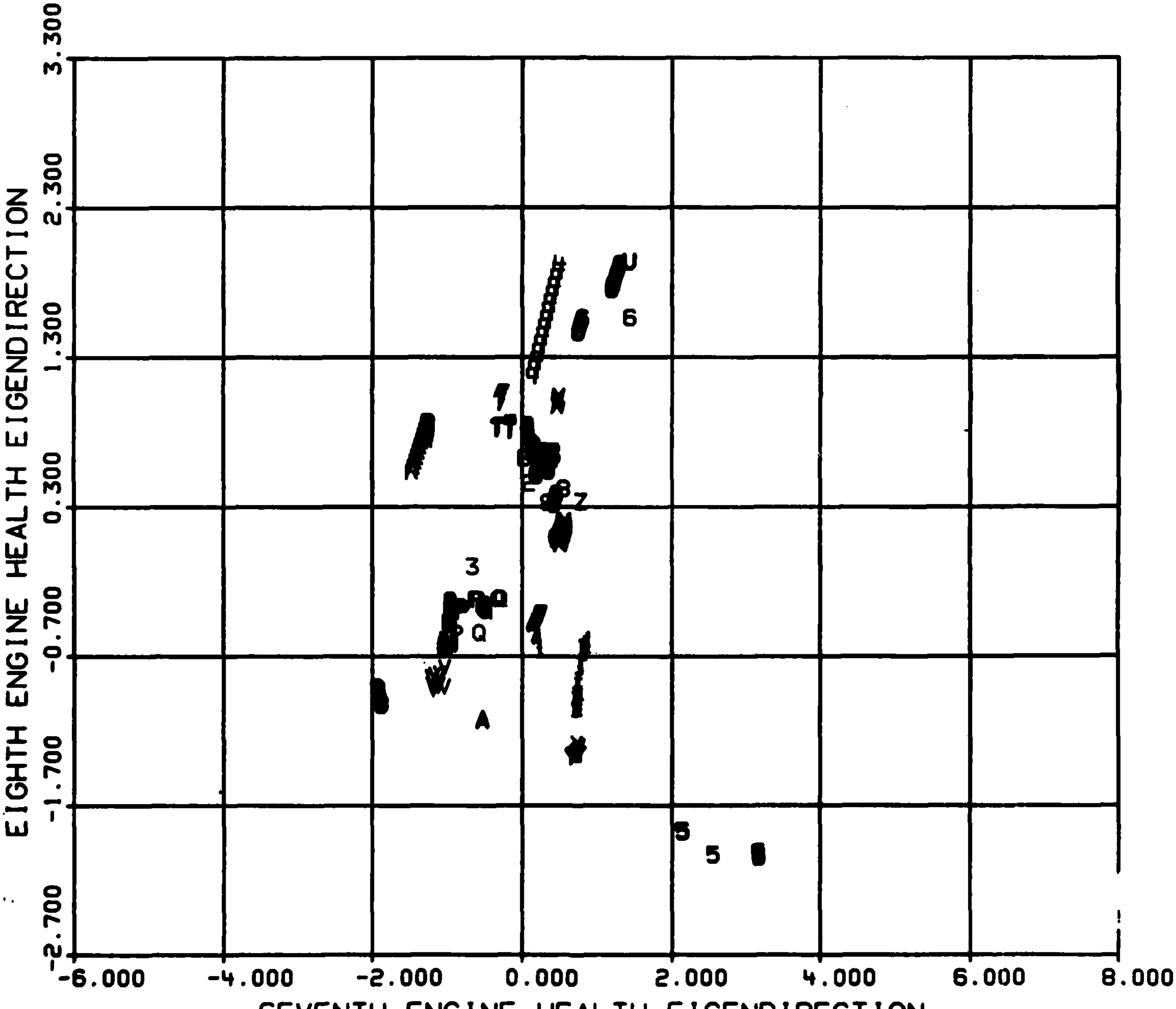


FIG-D3 PROJECTION ON SEVENTH AND EIGHTH HEALTH EIGENDIRECTION



BSE = 41.00

23 AUG 1982

FIGURE D4 - DEFINITION OF DOMINANT EIGENVECTOR OR EIGENDIRECTION

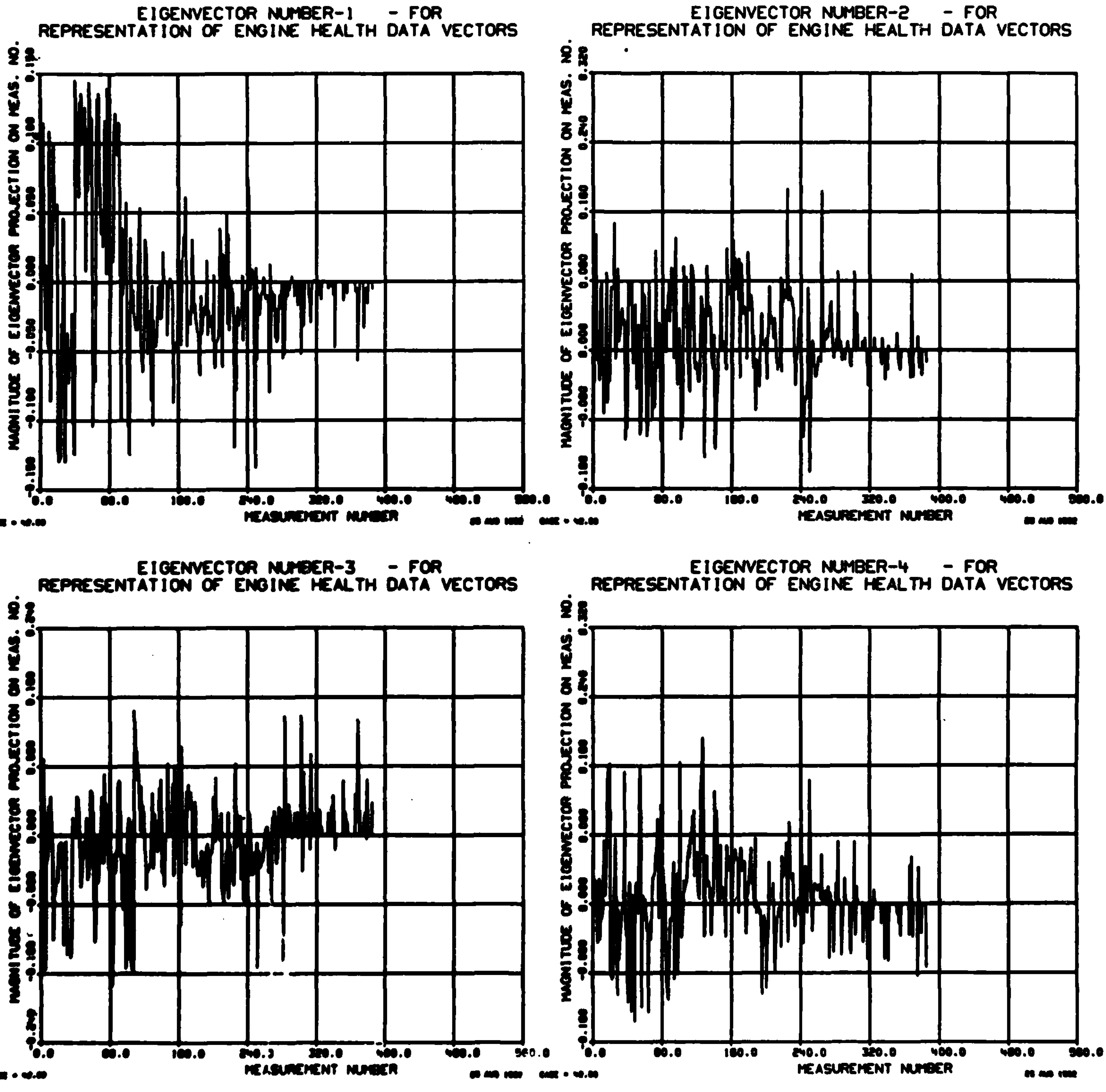


FIGURE D4 (CONT'D) - DEFINITION OF DOMINANT EIGENVECTOR OR EIGENDIRECTION

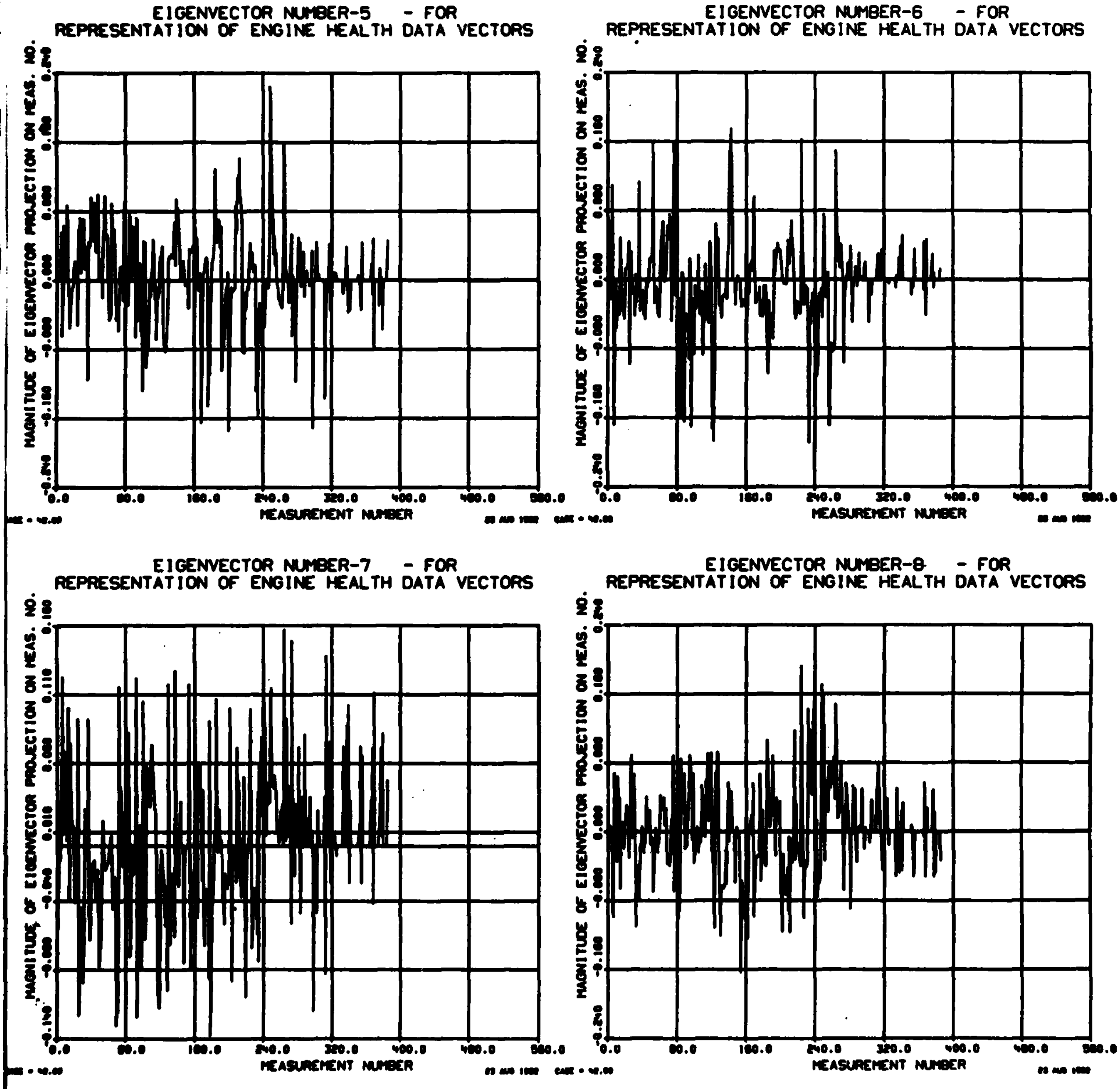


FIGURE D5 - EIGENVECTOR ILLUSTRATING CHANGE FROM INTERMEDIATE TO HIGH ORDER CHARACTER OF THE EIGENVECTORS

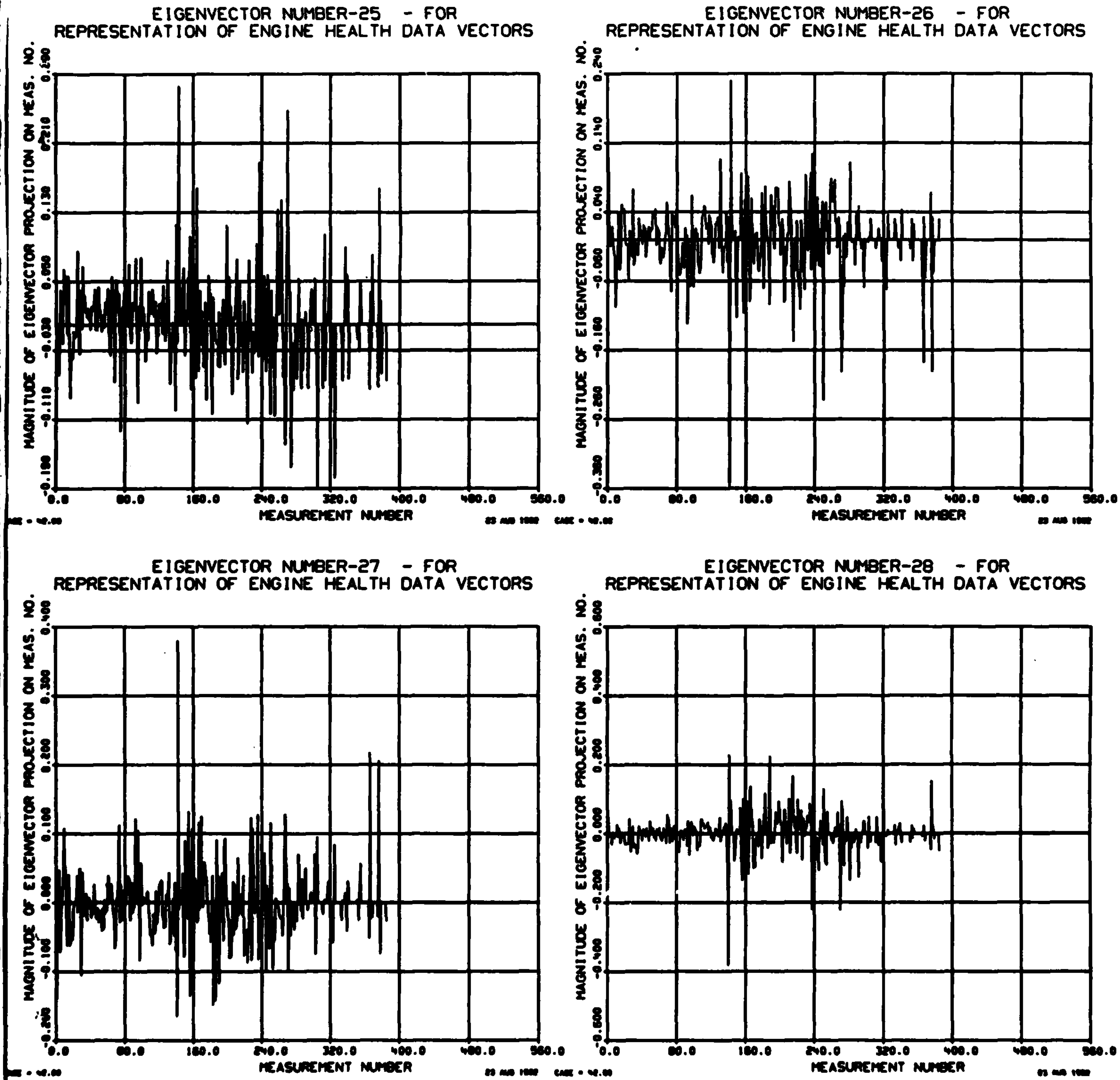


FIGURE D6 - TYPICAL HIGHER ORDER EIGENVECTORS